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Field Phenotyping of Seven Malaysian Coconut Varieties for Yield Traits

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ABSTRACT

Although the coconut (*Cocos nucifera* L.) is of economic importance, the industry poses challenges of low productivity and limited seedling availability. This study utilised field phenotyping to evaluate the yield characteristics of four tall and three dwarf coconut varieties across three distinct locations in the West Coast regions of Peninsular Malaysia. A total of 210 samples, representing seven varieties, were collected using a nested design methodology. The analysis of the mean comparison between Malayan Yellow Dwarf (MYD) and Malayan Red Dwarf (MRD) varieties reveals that MYD exhibits a smaller leaf area but a faster maturation rate, whereas MRD demonstrates a greater leaf area and undergoes a slower maturation process. A yield trait comparison between Pandan and Tagnanan (TGG) shows Pandan having a significantly higher nut yield, while both varieties exhibit a similar maturation rate. Additionally, the mean comparison of yield traits of Malayan Tall (MT), Ceylon Tall (CT), and Rennell Tall (RT) indicates that all varieties have similar rates of maturation and average nut yield per year, but different values of Standing Stem Dry Weight (SSDW) and Projected Leaf Area (PLA). Notably, RT exhibits a unique trait of having the lowest PLA among the three varieties. The correlation analysis identifies SSDW as the key factor for average nut yield per year in MRD, Pandan, and RT, as well as for maturation rate in MYD, MRD, and CT. In summary, the findings of this study can be leveraged for informed decision-making and strategic cultivation practices in the Malaysian coconut industry.

Keywords: Aerial images, coconut, field phenotyping, precocity assessment, UAV, yield traits

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INTRODUCTION

Coconut (*Cocos nucifera* L.) is a monocotyledonous perennial palm that belongs to the sub-family Cocoideae, which includes 27 genera and 600 species (Teulat et al. 2000). It is the only species within the genus Cocos and has 32 chromosomes (2n = 16) (Khairun et al., 2016). The primary taxonomic classification of coconut presents two varieties: tall and dwarf. The tall variety is characterised by cross-pollination, heterozygosity, a long lifespan, and slow maturation. Conversely, the dwarf variety is characterised by self-pollination, homozygosity, and a faster maturation rate than the tall variety (Perera et al., 2010). Dwarfs are typically found in close proximity to human settlements and display traits that are reflective of human selection, such as slow trunk growth and self-pollination (Alrifai & Marcone, 2019). In contrast, tall varieties demonstrate a wild-type phenotype with high phenotypic expression for all metrical traits and lack self-pollination (Raveendra et al., 2010). Given its multifaceted uses and the potential for human utilisation of every part of the plant, the coconut is commonly dubbed the "tree of life” (Burkill et al., 1966).

Coconut plays an important role in the agricultural landscape of Malaysia as it is ranked the fourth most important crop in terms of area planted after oil palm, rubber, and paddy (Yun, 2019). In 2022, coconut cultivation in Malaysia covered an estimated 84,935.9 hectares, with approximately 64,837 farmers engaged in its production. The coconut productivity in this reported year was 8.3 tan/ha, resulting in a total production of 604,428.4 metric tons (Ministry of Agriculture and Food Security, 2023). Coconut breeding has traditionally focused on the attainment of high nut yield as its primary objective, with subsequent priorities including precocity, reduced plant height, and improved resistance to biotic and abiotic stresses (Perera, 2012).

Malaysia has significant potential to increase its coconut productivity. This is because a large proportion of the existing coconut trees are senile and no longer productive (Abu Dardak & Mohd Yon, 2021). So, an overall increase in coconut yield is possible by replacing these trees with younger and more productive ones. Additionally, some coconut varieties have inherently low yield potential (Sivakumar et al., 2020). If farmers lack access to higher-yielding varieties, the consequences would be an overall reduction in coconut productivity. Planning for a large-scale replanting program with elite varieties with desirable traits, such as higher yield, becomes a distant goal because of the limited availability of quality seedlings. The limited availability of quality seedlings further hinders farmers' ability to replant senile trees with more productive ones. These issues highlight the need to address the challenges facing coconut farming in Malaysia. Therefore, expanding replanting initiatives is essential for revitalising the coconut sector and meeting current market demands. However, achieving this on a large scale remains a challenging goal.

This study highlights critical aspects of coconut germplasm conservation and utilisation. Exploration of yield traits in Malaysian coconut germplasm materials is a way to identify and safeguard genetic diversity within the Malaysian coconut gene pool.

Besides this, the current study aims to identify high-yielding coconut germplasm materials that can be applied in breeding programs, contributing to increased coconut production. Identifying high-yielding coconut germplasm materials can improve farming practices by allowing more coconuts to be produced on less land, which also contributes to sustainable agriculture. In the future, the use of data analytics, especially linear regression, may help develop predictive models that enhance research outcomes and estimate productivity more accurately.

This study systematically examines phenotypic variations in yield traits among seven selected Malaysian coconut germplasm materials, which include four tall varieties: Malayan Tall (MT), Rennell Tall (RT), Ceylon Tall (CT), and Tagnanan Tall (TGG), as well as three dwarf varieties: Pandan, Malayan Yellow Dwarf (MYD), and Malayan Red Dwarf (MRD). While past studies have primarily focused on molecular markers or limited field trials, our study offers a more thorough evaluation of yield traits through field phenotyping. Using this method, we gained a clearer understanding of germplasm potential, which can guide breeding efforts to develop higher-yielding coconut varieties. Current research marks the first comprehensive morphological assessment of coconut germplasm within the Department of Agriculture of Malaysia's repository, which was evaluated through a newly developed observational pipeline. Utilising unmanned aerial vehicles (UAVs) and cutting-edge open-source software, we collected and analysed reflectance data to estimate leaf area. These approaches provide a foundation for integrating advanced phenotyping techniques and tools into coconut research programs.

MATERIALS AND METHODS

Selection of Coconut Palms

A total of seven plots were identified within three agricultural centres under the Department of Agriculture of Malaysia (DOA), focusing on the data collection of seven coconut varieties: Malayan Red Dwarf (MRD) and Malayan Yellow Dwarf (MYD) at Agriculture Centre Lekir, Perak; Pandan and Tagnanan (TGG) at Agriculture Centre Teluk Bharu, Perak; as well as Malayan Tall (MT), Ceylon Tall (CT), and Rennal Tall (RT) at Agriculture Centre Parit Botak, Johor. Varietal comparisons were conducted only among palms grown under the same site and management conditions within each location (MRD and MYD at Lekir-Pandan; Pandan and TGG at Teluk Bharu; MT/CT/RT at Parit Botak). We did not compare varieties across sites. A total of 210 samples, comprising seven varieties, each with 30 nested samples, were selected, utilising a nested design approach. n = 30 per variety follows standard coconut germplasm evaluation (Santos et al., 1996) and was the maximum feasible due to limited uniform mature palms and labour-intensive phenotyping. This provided power to detect large differences (e.g., nut yield Pandan vs. TGG), though larger n would refine intravarietal variation estimates.

Palms were from the same germplasm block and planting year according to the DOA database. Physiological age was verified by trunk height and length of 11 leaf scars, and atypical or stressed palms were excluded. It should be noted that location effects, particularly when comparing tall versus dwarf varieties, cannot be fully separated from varietal effects. However, soil physicochemical properties were not measured at each site. Unmeasured soil variability may contribute to variation in SSDW and nut yield that is not due to genetics. Future studies should incorporate soil analysis, which clarifies how much of the variation is due to environmental factors.

Determination of Standing Stem Dry Weight (SSDW)

A non-destructive approach was used to determine the dry weight of standing stems. The stems' vertical height was measured from the ground to the base beneath the crown. For taller palms exceeding 3 meters, an unmanned aerial vehicle (UAV) model SJRC F11 4K Pro was employed for height measurement. To ensure reliable measurements, several validation steps were conducted. First, ground measurements were manually taken for palms shorter than 3 m to cross-check the UAV estimates. Besides this, UAV flights followed a consistent protocol, such as the camera being aligned parallel to the stem and flown vertically to the crown base, with GPS altitude hold and a gimbal used to reduce positional error. Finally, measurements were repeated across flights to check for consistency. It should be noted that formal statistical validation, such as regression between UAV and ground measurements, was not performed. Future studies should include systematic ground-truth calibration across different height classes.

The stem circumference was recorded at two specific points, namely 20 cm and 1.5 m above ground level, to obtain these measurements. A measuring tape was carefully wrapped around the stems of 30 selected palm trees from each variety. The calculation for SSDW was performed according to a method developed by Naresh et al., (2008), as shown in Equation 1:

$$\text{SSDW (kg)} = \text{Length (in m)} * \text{girth}^2 \text{ (in m, at 1.5 m above ground level)} * 41.14142 \qquad [1]$$

The coefficient 41.14142 is pertinent for palm trees taller than 1.5 meters. For palms below 1.5 meters, a correction factor (F) was computed and employed in the SSDW calculation for dwarf palm trees, as outlined in Equation 2:

$$\text{SSDW (kg)} = \text{Length (in m)} * \text{girth}^2 \text{ (in m, at 20 cm above ground level)} * (H/1.5) * 41.14142 \qquad [2]$$

where, H = Individual stem height

The correction factor considers the differences in measurement height (20 cm above ground) and scales the girth measurement to what it would have been at 1.5 meters. By including the correction factor, the height difference was addressed, and the formula was made applicable to shorter palm trees.

Determination of the Length of 11 Leaf Scars

The length of 11 leaf scars was measured by recording the distance between the bottom of scar number 1 (above ground) and the bottom of scar number 11 using a measuring tape (Santos et al., 1996).

Determination of the Estimated Number of Fruits Per Bunch

The number of fruits per bunch was estimated by selecting three of the most mature bunches and visually counting the fruits with the eye from the ground. The recorded values were used to calculate the average number of fruits per bunch. This process of fruit estimation was repeated over six consecutive readings, taken at bimonthly intervals for dwarf, and monthly intervals for tall (Santos et al., 1996). The average number of fruits per bunch was recorded for each reading.

The yearly average was determined using a customised calculation method of Santos et al. (1996), specifically tailored to align with the research objectives and accommodate resource constraints as stated below in Equations 3 and 4:

$$\text{Tall: Estimated Number of Fruit per Bunch year-1} = \Sigma\ ((\bar{y}_1 + \bar{y}_2 + \bar{y}_3 + \bar{y}_4 + \bar{y}_5 + \bar{y}_6) / 6) *12 \qquad [3]$$

$$\text{Dwarf: Estimated Number of Fruit per Bunch year-1} = \Sigma\ ((\bar{y}_1 + \bar{y}_2 + \bar{y}_3 + \bar{y}_4 + \bar{y}_5 + \bar{y}_6) / 6) *2*12 \qquad [4]$$

where, $\bar{y}i$ is the individual average yield.

Determination of Total Leaf Area

Leaf area (crown) of each palm was determined by employing image data acquisition and analysis through the utilisation of Plant Screen Mobile (PSM) (Müller-Linow et al., 2019), a smartphone application designed to estimate proxies of leaf area in diverse imaging situations, including field conditions. Image acquisition for tall palm trees was conducted using the UAV model SJRC F11 4K Pro, while images for dwarf palm trees were captured using smartphones, as the use of drones was not practical. In both scenarios, smartphones with identical camera calibrations were employed. Image post-processing was conducted for leaf area proxy estimation via the PSM app (Figure 1). The processed images were transformed into a CSV file by the PSM application, facilitating the extraction of the Projected Leaf Area (PLA) for each individual sample.

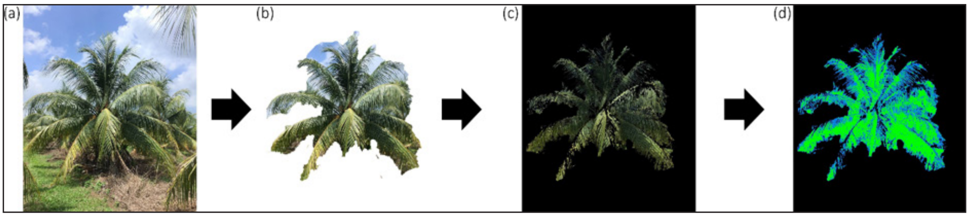

Figure 1. Steps of image post-processing and analysis using the Plant Screen Mobile App. (a) An image of sampled palms was captured, primarily focused on the crown. (b) AI-incorporated tools were employed to achieve precise extraction of specific sections within images. (c) The Plant Screen Mobile app used image masking in image processing to selectively conceal or reveal specific regions based on a selected greenness segmentation algorithm for precise manipulation and isolation of areas of interest in the image. (d) Plant Screen Mobile facilitated trait analysis and the development of proxies for total leaf area measured in pixels per square millimetre

Statistical Analysis

The Shapiro-Wilk test was performed for each set of yield trait data to assess its normality. In instances where datasets exhibited adherence to normal distribution, an independent samples t-test was employed to investigate significant differences between the means of two independent groups. Similarly, the one-way analysis of variance (ANOVA) was employed to assess the impact of multiple factors on the observed data when three factors were under analysis. Subsequently, post hoc testing was conducted using the Tukey Honestly Significant Difference (HSD) test to compare means, depending upon the detection of significant differences in the ANOVA. If the data for the yield trait did not show a normal distribution, non-parametric tests were employed. The Mann-Whitney U test was utilised to ascertain significant differences in cases where comparison was limited to two varieties. For analyses involving more than two varieties, the Kruskal-Wallis test is used for comparison. Afterwards, post hoc comparisons were performed using the Dunn test to examine differences in mean ranks whenever the Kruskal-Wallis test indicated significant variation. Data was analysed in two stages. First, an overall test (ANOVA or Kruskal-Wallis) was conducted for each trait. When significant differences were observed, post hoc pairwise comparisons were carried out using Tukey HSD for ANOVA and the Dunn test for Kruskal-Wallis to control family-wise error. No additional corrections were applied across traits, as each trait represents a distinct biological outcome. Sample sizes were balanced, with 30 individuals per variety at each site, providing sufficient power to detect moderate to large differences. Some comparisons, such as nut yield among MT, CT, and RT varieties, were not significant, possibly due to variance limiting detectability. Confidence intervals were not reported in this study but would help quantify estimation precision beyond p-values. Future analyses will include confidence intervals alongside mean comparisons and statistical tests.

RESULTS AND DISCUSSION

The Shapiro-Wilk test confirmed that the MYD and MRD varieties grown at Agriculture Centre Lekir, Perak, exhibited normal distribution for all yield traits, except the length of 11 leaf scars ($p < 0.05$) (Table 1). Therefore, an independent t-test was applied for the analysis, except for the length of 11 leaf scars, which underwent a Mann-Whitney U test

Table 1

Normality assumption of the yield trait data of seven coconut varieties at three different locations using the Shapiro-Wilk test

Yield Trait	Location	Variety	Shapiro-Wilk Test Statistic (W)	p-value	Interpretation of Normality
Average nut yield per year	Agriculture Centre Lekir, Perak	MYD	0.95	0.16	Normal
		MRD	0.95	0.15	Normal
	Agriculture Centre Teluk Bharu, Perak	Pandan	0.91	0.01	Not normal
		TGG	0.94	0.08	Normal
	Agriculture Centre Teluk Bharu, Johor	MT	0.96	0.25	Normal
		CT	0.93	0.06	Normal
		RT	0.95	0.14	Normal
Standing stem dry weight	Agriculture Centre Lekir, Perak	MYD	0.96	0.32	Normal
		MRD	0.93	0.06	Normal
	Agriculture Centre Teluk Bharu, Perak	Pandan	0.99	0.94	Normal
		TGG	0.68	0.00	Not normal
	Agriculture Centre Teluk Bharu, Johor	MT	0.94	0.12	Normal
		CT	0.97	0.57	Normal
		RT	0.95	0.18	Normal
Projected leaf area	Agriculture Centre Lekir, Perak	MYD	0.97	0.49	Normal
		MRD	0.99	0.96	Normal
	Agriculture Centre Teluk Bharu, Perak	Pandan	0.96	0.94	Normal
		TGG	0.81	0.00	Not normal
	Agriculture Centre Teluk Bharu, Johor	MT	0.87	0.00	Not normal
		CT	0.78	0.00	Not normal
		RT	0.69	0.00	Not normal
Length of 11 scars	Agriculture Centre Lekir, Perak	MYD	0.94	0.09	Normal
		MRD	0.85	0.00	Not normal
	Agriculture Centre Teluk Bharu, Perak	Pandan	0.91	0.02	Not normal
		TGG	0.96	0.23	Normal
	Agriculture Centre Teluk Bharu, Johor	MT	0.95	0.57	Normal
		CT	0.94	0.11	Normal
		RT	0.96	0.30	Normal

Note. MYD = Malayan Yellow Dwarf, MRD = Malayan Red Dwarf, TGG = Tagnanan, MT = Malayan Tall, CT = Ceylon Tall, RT = Rennell Tall

(Figure 2). For average nut yield per year and SSDW, the independent t-test did not reveal significant differences between the two varieties ($p = 0.87$ and $p = 0.20$, respectively, both $p > 0.05$), indicating that the yields of both varieties were similar. However, for PLA, the independent t-test indicated a statistically significant difference ($p = 0.04$, $p < 0.05$), suggesting different performance between MYD and MRD varieties in this regard. Specifically, the MRD exhibited significantly higher values in both PLA and the length of 11 leaf scars as compared to MYD. These findings suggest that leaf growth does not significantly impact the storage of dry matter and soluble carbohydrates in the stem for both varieties examined. These results are consistent with prior research that suggests a reduction in leaf area does not exert a significant effect on the carbohydrate reserves stored in the stem (Mialet-Serra et al. 2008). In addition, palms with larger leaf areas in the MRD group demonstrated a slower rate of maturation, while palms with smaller leaf areas in the MYD group showed a faster maturation rate. The limited existing literature on the relationship between fast maturation and leaf area in dwarf varieties suggests that these findings could provide preliminary insights into how to accelerate maturity in both varieties. Based on the available information, it can be inferred that MYD reaches maturity faster than MRD, with no significant difference in nut production between MRD and MYD. In the case of the length of 11 leaf scars, the Mann-Whitney U test demonstrated a highly significant difference ($p = 5.39 \times 10^{-6}$, $p < 0.05$) between the two varieties.

In contrast to MYD and MRD, the Shapiro-Wilk test indicated non-normal distributions ($p < 0.05$) across all examined yield traits in Pandan and TGG varieties at Agriculture Centre Teluk Bharu, Perak (Table 1). Therefore, the Mann-Whitney U test was used for further analysis, which revealed significant differences between the two varieties for

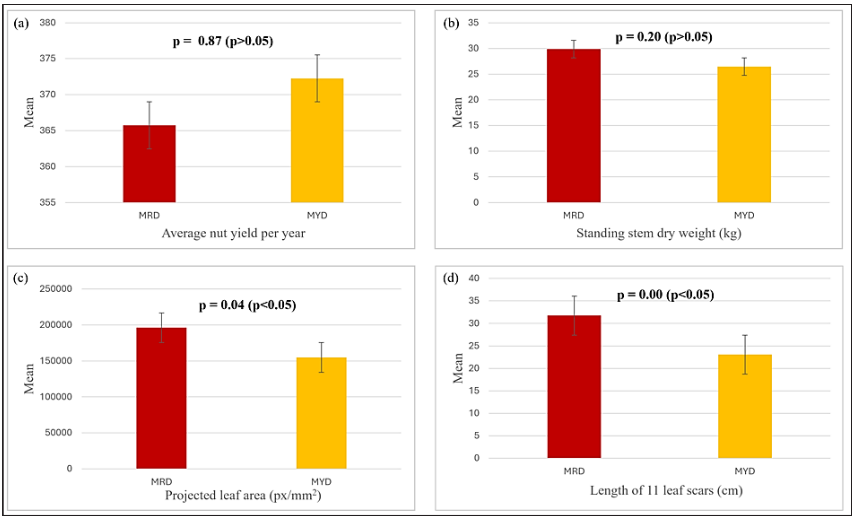

Figure 2. Comparative analysis of yield traits between Malayan Yellow Dwarf (MYD) and Malayan Red Dwarf (MRD) varieties

average nut yield per year ($p = 7.37 \times 10^{-11}$) and SSDW ($p = 1.21 \times 10^{-10}$) (Figure 3). Pandan demonstrates higher values in both aspects, indicating potential productivity advantages. Three Pandan palms, namely palm 01/0089, palm 01/0096, and palm 01/0103, yielded exceptionally high nut yields of 744, 720, and 708 nuts per palm per year, respectively. These yields represented increases of approximately 54%, 49%, and 46%, respectively, compared to the average nut yield per year of 483.6 nuts/palm/year for the Pandan variety. In contrast, palm 02/0057 of the TGG variety produced only 32 nuts per palm per year, compared with the variety's average of 162.8 nuts per palm per year. Therefore, this palm showed approximately an 80.42% decrease in nut yield compared to the mean nut yield of the TGG variety. These results are consistent with earlier findings, which reported yield potential and yield gap ranging from 31% to 87% (Crisostomo et al. 2023). Expanding on the findings of prior research (Thomas et al. 2005), which identified dry matter production and efficient distribution as pivotal for coconut palm productivity, our study demonstrates Pandan's high nut yield despite markedly lower SSDW, contrasting with TGG's lower nut yield with high SSDW. This suggests that Pandan efficiently allocates energy to nut production, effectively converting stem-stored soluble sugars into yield.

As for PLA and the length of 11 leaf scars, no significant differences were observed, with a p-value of 0.44 and 0.09, respectively. Pandan, a variety that originated in Thailand as a spontaneous mutation of the green dwarf type (Dumhai et al. 2019), demonstrates a maturation rate similar to that of TGG, a tall variety as observed in this study. This similarity in maturation rates may be attributed to its cultivation in regions far from its native origin. The maturation rate of Pandan outside its place of origin has not been documented in previous research, highlighting a gap in existing studies.

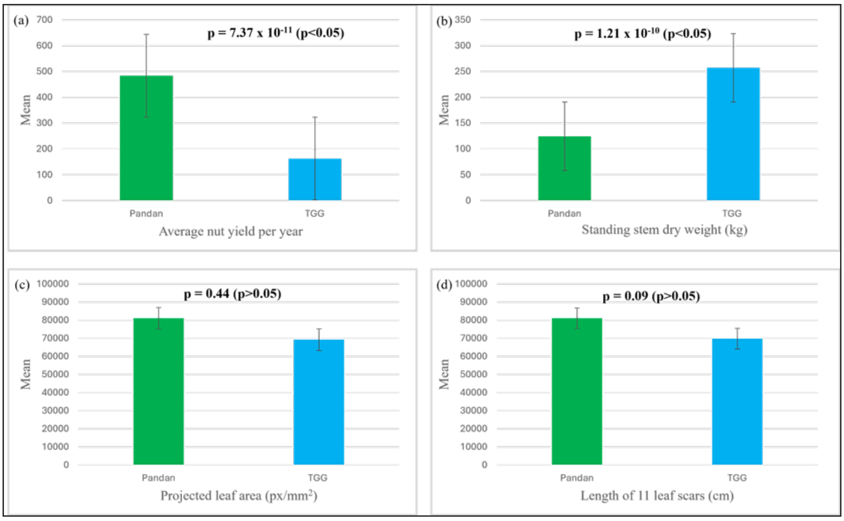

Figure 3. Comparative analysis of yield traits between Pandan and Tagnanan (TGG) varieties

Next, since the datasets of MT, CT, and RT varieties grown at the Agriculture Centre, Teluk Bharu, Johor showed normal distributions across all yield traits ($p > 0.05$), except for PLA ($p < 0.05$) (Table 1), ANOVA was utilised for statistical analysis. In the case of PLA, the Kruskal-Wallis test was employed. The ANOVA test conducted on the average nut yield per year of MT, CT, and RT varieties yielded a p-value of 0.04 ($p < 0.05$), indicating a significant difference among the groups (Figure 4). Similarly, for the SSDW of MT, CT, and RT varieties, the ANOVA test resulted in a p-value of 6.44 x 10^{-11} ($p < 0.05$), indicating a significant difference between the groups. However, for the length of 11 leaf scars, the ANOVA test produced a p-value of 0.80 ($p > 0.05$), indicating no significant difference among the groups. In contrast, the Kruskal-Wallis test conducted on the varieties MT, CT, and RT for the parameter PLA yielded a p-value of 6.06 x 10^{-4} ($p < 0.05$), indicating a significant difference among the groups.

Additional analysis was conducted through post hoc testing (Figure 5) on the average nut yield per year and SSDW, both employing Tukey's Honestly Significant Difference (HSD), and PLA with Dunn’s test. This analysis was conducted to identify significant differences among groups, helping to draw more precise conclusions about the relationships between variables. The mean comparisons for average nut yield per year (Figure 5a) revealed differences of 4.80 between MT and CT, 43.67 between MT and RT, as well as 38.87 between CT and RT. These differences fall below the HSD 0.05 threshold of 44.45. Consequently, no significant differences were observed among the analysed pairs of MT-CT, MT-RT, and CT-RT at the 0.05 significance level, suggesting that the three varieties have comparable nut yields.

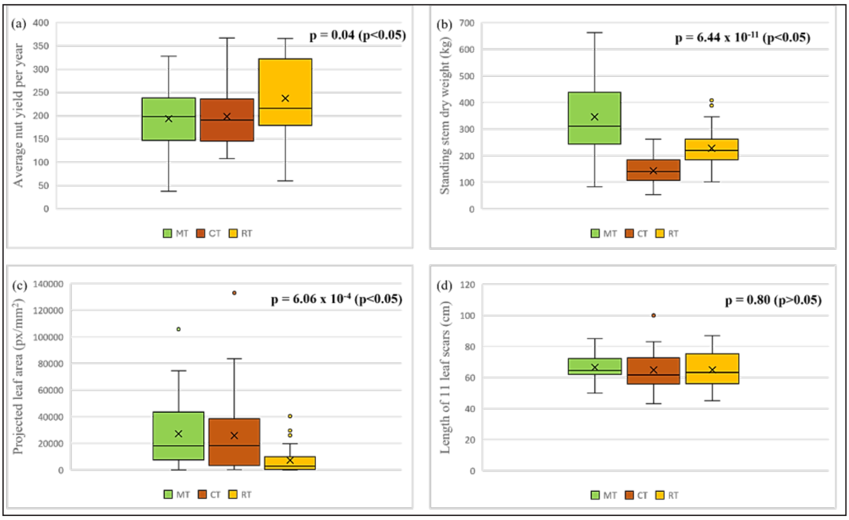

Figure 4. Comparative analysis of yield traits in Malayan Tall (MT), Ceylon Tall (CT), and Rennell Tall (RT) varieties

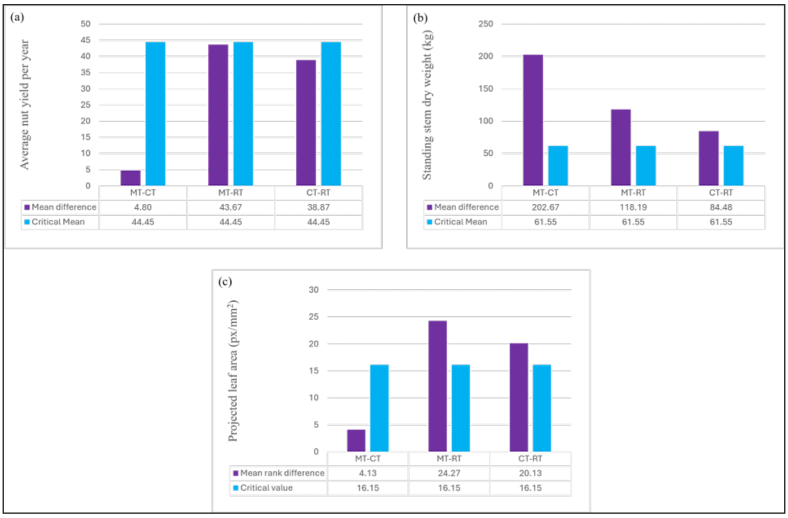

Figure 5. Comparisons of average nut yield per year, Standing Stem Dry Weight (SSDW), and Projected Leaf Area (PLA) among Malayan Tall (MT), Ceylon Tall (CT), and Rennell Tall (RT) varieties

In the comparison of mean SSDW among MT, CT, and RT varieties, all pairwise comparisons exhibited significant differences between their respective means (Figure 5b). The mean differences surpassed the critical value of HSD 0.05 at 61.56. Specifically, the mean differences for MT and CT, MT and RT, as well as CT and RT were 202.67, 118.19, and 84.47, respectively. The mean rank difference analysis for PLA across MT, CT, and RT varieties indicated significant differences in the mean ranks of the MT and RT pair (mean rank difference: 24.27 > critical value: 16.15) and the CT-RT pair (mean rank: 20.13 > critical value: 16.15) (Figure 5c). Conversely, no significant difference was observed in the MT-CT pair, with a mean rank difference of 4.13 < critical value: 16.15. The findings of the current study suggest that while there is variation in dry matter accumulation (SSDW) and PLA, the nut yield remains similar among the three tall palms, possibly due to shared characteristics such as soil nutrient extraction ability and comparable photosynthetic energy allocation toward nut yield. This variation in SSDW and PLA is aligned with previous research that suggests coconut, being less domesticated, still possesses characteristics inherited from its wild ancestors, leading to non-uniform vegetative growth (Foale, 2003). Nevertheless, the variation in the dry matter accumulation in the stem and leaf area among these three varieties suggests a consistent trend. However, these variations do not result in differences in nut yield among the three tall varieties.

The limitation of this study is that each variety was evaluated at a single location. This restricts how well the findings can be generalised across Malaysia's diverse agro-climatic zones and the range of management practices used on different farms. Therefore, multi-location trials are needed to better capture genotype × environment interactions and provide more robust recommendations for coconut varieties.

Correlation analyses were performed to investigate the dependency and potential influences among several growth and yield traits of coconut varieties. These traits include the average nut yield per year, SSDW, PLA, and the length of 11 leaf scars (Figure 6). Notably, the present investigation reveals a strong positive correlation between SSDW and the average nut yield per year in MRD, Pandan, and RT (Figure 6), **s**uggesting a potential physiological link whereby higher stem dry matter accumulation may reflect greater carbohydrate storage available for reproductive growth. We cannot conclude that one factor causes another based on correlation alone. Future studies, such as path analysis or controlled experiments, are needed to better understand how stem dry matter accumulation influences nut yield efficiency. This correlation serves as an initial step in understanding the association between stem dry matter accumulation and its allocation towards nut production across the examined varieties. Previous literature suggests that the stem functions as a storage site for soluble sugars, particularly sucrose (Mialet-Serra et al., 2005). Carbohydrates are stored in the stem for medium-term storage, which predominantly benefits the plant during periods of increased energy demand, such as seed development or in response to drought-

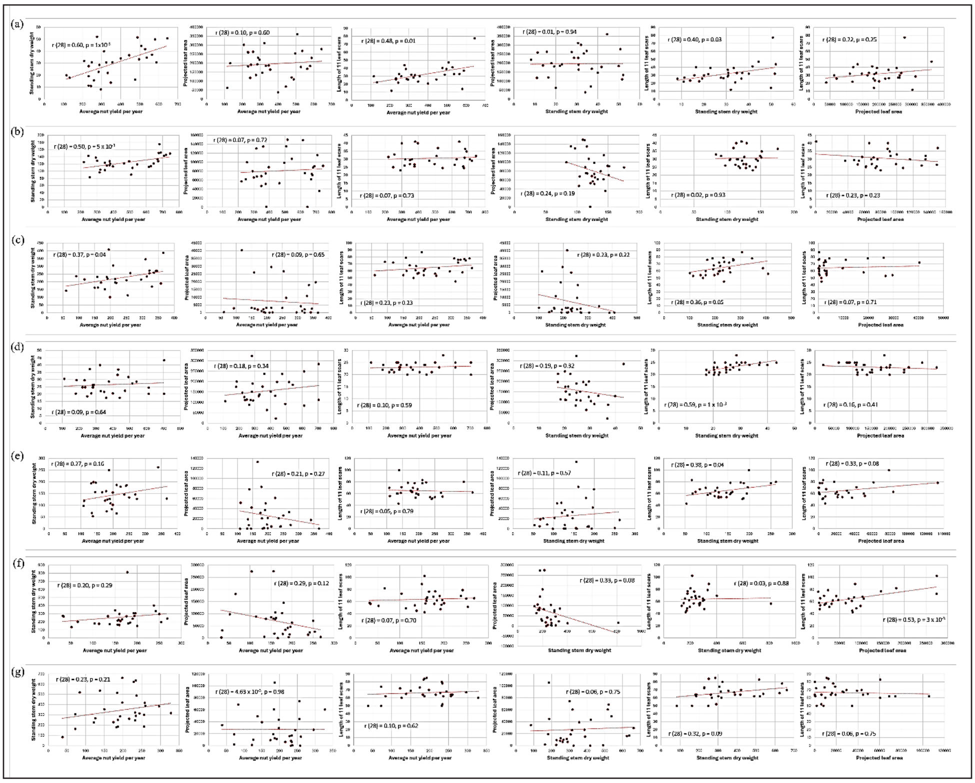

Figure 6. Correlation graphs illustrating the correlation coefficient between the yield traits of (a) Malayan Red Dwarf, (b) Pandan, (c) Rennel Tall, (d) Malayan Yellow Dwarf, (e) Ceylon Tall, (f) Tagnanan Tall, (g) Malayan Tall varieties

induced water stress (Kozlowski, 1992; Loescher et al., 1990; Oliveira & Priestley, 1988). In tropical regions where coconut trees thrive, the stored carbohydrate in the stem remains to play a significant role, despite relatively stable environmental conditions. Although coconut trees are known for their continual fruit production and ability to remain green throughout the year, it is vital to maintain carbohydrate reserves in order to support growth and fruiting activities (Mialet-Serra et al., 2005). However, there is a lack of studies on the relationship between the stem dry matter accumulation and the nut yield across specific varieties, thereby creating gaps in the knowledge of varietal-specific growth and fruiting dynamics. The present study has addressed this gap by identifying the specific variety which has the most efficient translation of stem dry matter to nut yield.

Next, the length of 11 leaf scars was examined to evaluate how the rate of maturation affects the overall growth and fruiting dynamics of each variety. These findings may facilitate the selection of palms that can produce fruit earlier and yield more nuts, supported by empirical evidence. Out of the seven varieties, only MRD demonstrates a noteworthy positive correlation between the length of 11 leaf scars and the average nut yield per year (Fig. 6). This implies that the slower maturation of MRD leads to an increase in the average nut yield per year, suggesting that the current study did not identify a variety that matures early and has a high yield. The length of 11 leaf scars is a key indicator in evaluating the growth pattern of coconut palms, indicating their precocious and early bearing nature (Mohamad Zaki et al., 2023). The initial inflorescence usually emerges in conjunction with the fronds, typically situated between the 10th and 12th frond positions (Foale, 2003). Previous studies, as well as the farmers' interests, were mostly focused on identifying coconut palms with short stems and early maturity that exhibit quick fruit-bearing capabilities exclusively (Novarianto et al., 2016). Although Bido Tall, a variety from Indonesia, has been described as having a short stem, faster maturation, and abundant yield compared to other tall varieties (Novarianto et al., 2016), there is little evidence to support its correlation with early bearing nature and yield potential. This study represents the first comprehensive investigation into the early bearing capacity in relation to nut yield.

Investigating the correlation between SSDW and the length of 11 leaf scars in the seven varieties of coconut palms in the present study holds promise for interpreting several factors of plant physiology and growth dynamics. This includes understanding nutrient partitioning, which refers to the distribution of soluble sugars in coconut palms that might explain the resource allocation within the plant. Examining the correlation with maturation rate could reveal whether faster-maturing palms use different strategies for sugar accumulation and distribution compared to slower-maturing palms. This study may help us understand how coconut palms cope with stress. The results of the present study reveal a positive correlation between SSDW and the length of 11 leaf scars in the MRD, MYD, and CT varieties (Figure 6). This suggests that in these three varieties, increased accumulation of dry matter in the stem is associated with a slower maturation. Previous findings show that carbohydrate reserves function like signalling molecules, influencing various developmental and physiological processes within the plant (Mialet-Serra et al., 2005; Luquet et al., 2007). When plants have plenty of carbohydrate reserves, they often use these resources to grow more leaves or flowers. In contrast, if reserves are low, growth and maturation slow down until conditions improve and carbohydrates can be replenished. This phenomenon is referred to as sugar signalling (Roitsch et al., 2000; Rolland et al., 2002; Gupta & Kaur, 2005). Essentially, these carbohydrate stores facilitate plant adaptation to environmental fluctuations, serving as a form of resilience during challenging conditions (Wingler et al., 2006).

Examining the relationship between PLA and the length of 11 leaf scars provides a way to evaluate growth rate and understand how leaf size corresponds to scar length. This knowledge is crucial for understanding growth dynamics. Furthermore, the findings can be used for predictive modelling, where PLA's predictive capacity regarding scar length can inform models for forecasting maturation rates. The findings of the present study unveiled that only the TGG variety exhibits a significant positive correlation between PLA and the length of 11 leaf scars (Figure 6). This suggests that an augmentation in leaf area is associated with a deceleration of the process of maturation, specifically in the TGG variety. Consequently, it implies that a reduced efficacy in light interception during the transition from the juvenile phase to the productive stage may underline the observed phenomenon of slowed growth in TGG. Previous literature, as emphasised by Foale (2003), suggests that the crown shape has an impact on the efficiency of light interception. The current findings indicate that rapid leaf growth potentially impedes the optimal photosynthetic capacity necessary for TGG's rapid maturation. The slow growth of coconuts during the juvenile phase is attributed to decreased photosynthetic rates caused by the self-shading effect of upper canopy fronds (Corley, 1983). Consequently, compared to other varieties, TGG exhibits a slower transition from the juvenile to production phase due to the rapid growth of leaves. Based on the Pearson correlation analysis, MT is the only variety among the seven varieties that shows an insignificant, small positive correlation between the six yield parameters (Figure 6).

This study presents a novel pipeline for high-throughput coconut phenotyping using UAVs, mobile applications, and AI tools, representing the first application of these technologies in this field. A key challenge in coconut phenotyping is the labour-intensive and time-consuming estimation of total leaf area and stem height measurement, especially for the tall varieties. The Standardised Research Manual in Coconut Breeding (STANTECH) adopted a non-destructive method for estimating total leaf area, a technique that was previously widely used for estimating the leaf area of oil palm (Hardon et al., 1969). This method has been enhanced in this study by integrating novel tools and software into the data collection process. The PSM, an Android-based mobile app, has the potential to make phenotyping coconut leafiness easier, faster, and more precise compared to the traditional methods (Müller-Linow et al., 2019). Integrating the PSM app with UAV technology is a novel approach for coconut phenotyping used in this study to capture and digitally measure proxies for the total leaf area of coconut palms, making measurements, especially for tall varieties, more accessible. Consequently, this pipeline for generating phenotyping data addresses the common bottleneck in coconut field phenotyping, enhancing data accuracy while reducing both time and cost associated with data collection (Arumugam & Md Hatta, 2022).

CONCLUSION

This study employs field phenotyping to evaluate yield traits in seven coconut varieties (four tall and three dwarf), sourced from DOA's germplasm collection. The findings indicate that MRD variety has a larger leaf area and a slower maturation rate compared to MYD, which exhibits a smaller leaf area but a faster maturation rate. Both MYD and MRD demonstrate similar nut yields. In MRD, yield traits are positively correlated with average nut yield per year, SSDW, and length of 11 leaf scars, while SSDW is positively correlated with the length of 11 leaf scars. In MYD, only SSDW is positively correlated with the length of 11 leaf scars. Pandan variety exhibits significantly higher nut yields compared to TGG, while TGG has a significantly higher SSDW value than Pandan. Pandan's exceptional nut yield, notably from palm number 01/0089, suggests that dry matter is effectively produced and allocated to support higher yield. Pandan and TGG show no significant differences in PLA and length of 11 leaf scars, indicating similar maturation rates despite their different statures.

Pandan's nut yield is positively related to SSDW, indicating effective production and distribution of dry matter. In TGG, PLA is positively correlated with the length of 11 leaf scars, suggesting faster maturation can be achieved with less leaf area without affecting nut yield. By comparing MT, CT, and RT, there are no distinctions in nut yield, but significant differences exist in SSDW and PLA. RT shows unique leaf development with the lowest means among the three varieties. The correlation analysis indicates that there is no association between yield traits in MT, while in RT, average nut yield per year is positively correlated with SSDW.

This study significantly advances coconut breeding programs by identifying high-yielding varieties and uncovering trait correlations. Future research will refine phenotyping strategies by integrating tools and technologies for high-throughput phenotyping, utilising innovative technologies for precise data collection and adapting to ongoing technological advancements. The outcomes lay a foundation for elucidating the molecular pathways and key genes underlying the coconut yield through the application of advanced omics technologies. It is crucial to select coconut palms with distinct phenotypes from the present study to perform future comprehensive investigations.

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DISCLAIMER

The authors confirm that no generative artificial intelligence (AI) tools were used in the writing, analysis, or preparation of this manuscript.

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