

Heat treatment responses in oil palm (*Elaeis guineensis*) genotypes and their impact on germination and seedling growth

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Abstract. Osei SA, Darkwah DO, Sapey E, Banafo SA, Ossom JS, Duah-Boateng I, Nyanful L, Francis O, Gyamerah EO, Godson A, Michael T, Kusan J, Fiawona B, Agyei-Dwarko D. 2026. Heat treatment responses in oil palm (*Elaeis guineensis*) genotypes and their impact on germination and seedling growth. *Asian J Agric* 10 (1): g100119. <https://doi.org/10.13057/asianjagric/g100119>. Seed dormancy in oil palm limits efficient propagation, necessitating optimized heat treatment to enhance germination and seedling growth. This study evaluated the effects of heat treatment duration and genotype using a 4×4 factorial randomized complete block design, involving four dura × pisifera hybrid progenies (61, 131, 132, and 136) and four heat durations (55, 60, 65, and 70 days). Key parameters measured included Germination Percentage (GP), Plant Height (PH), number of leaves, leaf length and breadth, butt circumference, Chlorophyll Content (CC, in SPAD units), and Stomatal Conductance (SC) were assessed under nursery conditions. Analysis of variance revealed significant progeny × duration interactions for GP, plant height, chlorophyll content, and stomatal conductance, indicating genotype-specific responses to heat treatment. Mean germination across treatments was high (90.52%), with the highest GP recorded in progeny 131 at 65 days (98.84%) and progeny 136 at 60 days (97.73%). Plant height varied significantly among treatments, reaching a maximum of 57.15 cm in progeny 131 at 60 days. In contrast, morphological traits such as leaf number, leaf size, and butt circumference showed no significant variation. Physiological traits were more responsive, with maximum chlorophyll content (54.31 SPAD units) and stomatal conductance (20.55 mmol m⁻² s⁻¹) observed in progeny 132 at 65 days. The results demonstrate that optimal heat treatment was identified as 60-65 days, with genotype-specific responses critical for maximizing germination and early seedling growth. The results could offer practical implications for certified seed production systems for maximizing germination efficiency and early seedling physiological performance in oil palm seed production systems.

Keywords: Dormancy, genotype, optimal, seedlings, trait

INTRODUCTION

The oil palm is a perennial oil-producing crop indigenous to the tropical rainforests of West and Central Africa. Among cultivated oil crops, oil palm remains unmatched in terms of oil yield per unit area, producing three to eight times more oil per hectare than soybean, rapeseed, or sunflower. This exceptional productivity, together with its capacity for year-round fruiting and a productive lifespan of up to 30 years, has established oil palm as a cornerstone of global vegetable oil supply. In addition to its central role in food systems, palm oil and palm kernel oil are indispensable raw materials in non-food industries, including soaps, cosmetics, pharmaceuticals, lubricants, and biofuels, underscoring the crop's broad economic significance (Barcelos et al. 2015; Murphy et al. 2020; John et al. 2022).

Despite these inherent advantages, oil palm production in Ghana remains considerably below its potential when compared with major producing countries such as Indonesia and Malaysia. Average national yields in Ghana are estimated at approximately 7 tons of Fresh Fruit Bunches (FFB) per hectare per year, far below the 20-25 tons per hectare commonly attained under optimal

management in leading producer countries (Rhebergen et al. 2018). This yield gap constrains the competitiveness of the sector and limits the contribution of oil palm to national income, rural livelihoods, and industrial development.

A major factor underlying this low productivity is the continued reliance on poor-quality planting materials, particularly uncertified seedlings and spontaneously regenerated “volunteer” palms. Such materials exhibit substantial genetic heterogeneity, resulting in uneven field establishment, delayed bearing, low bunch yield, and reduced oil content (Rhebergen et al. 2018). In response, national and regional strategies have increasingly emphasized the adoption of genetically improved planting materials, especially hybrids derived from dura × pisifera (D×P) crosses. These hybrids are widely recognized for their superior vigor, earlier fruiting, higher bunch weight, and improved oil extraction efficiency compared with unimproved or traditional planting materials (Bakoumé et al. 2017; Rhebergen et al. 2020). Initiatives such as Ghana's Planting for Export and Rural Development (PERD) program have actively promoted the use of elite hybrid seeds to revitalize the oil palm value chain and enhance smallholder productivity (MOFA 2020).

However, the large-scale dissemination of improved hybrid planting materials is constrained by the physiological dormancy of oil palm seeds. Under natural conditions, untreated seeds may require up to three years to germinate, rendering conventional propagation methods inefficient and impractical for commercial seed production (Beugré et al. 2009). Heat treatment has therefore become the most widely adopted and reliable approach for breaking dormancy in oil palm seeds. Standard protocols typically involve exposing seeds to temperatures of 38–40°C for 60–90 days, which accelerates embryo development and synchronizes germination by enhancing water and oxygen uptake (Norsazwan et al. 2020).

In Ghana, Ghana Sumatra Ltd. has recently explored slightly elevated thermal regimes ($41\pm 1^\circ\text{C}$) in an effort to reduce germination time further and improve uniformity in response to increasing demand for certified hybrid seeds. While such adjustments may offer practical advantages, empirical evidence on the agronomic consequences of higher or modified heat treatments remains limited. In particular, there is insufficient information on how variations in heat treatment duration influence seed viability, germination percentage, and early seedling growth under nursery conditions.

Moreover, existing germination protocols are generally applied uniformly across genotypes, despite indications that oil palm genotypes may differ in their responses to dormancy-breaking treatments. Variations in seed structure, dormancy intensity, and physiological sensitivity suggest that a single heat treatment regime may not be optimal for all hybrid progenies (Fondom et al. 2010). The lack of systematic evaluation of genotype-specific responses to heat treatment represents a critical knowledge gap, with important implications for the efficiency of seed production and the quality of planting materials supplied to farmers.

Addressing this gap is essential for developing refined, genotype-responsive heat treatment protocols that maximize germination efficiency and produce uniform, vigorous seedlings. Improved seedling establishment at the nursery stage is expected to translate into better field performance and enhanced productivity across the oil palm production system.

This study investigated the interactive effects of heat treatment duration and genotype on seed germination and early seedling growth of oil palm. Specifically, it assessed germination percentage, key morphological traits, and selected physiological parameters to identify optimal heat treatment durations and determine whether genotype significantly influences germination success and early growth performance.

Oil palm seed dormancy-breaking protocols are commonly applied uniformly across genotypes, despite evidence that genetic differences may influence physiological responses to heat treatment. This study hypothesized that oil palm *dura* × *pisifera* progenies differ significantly in their germination success and early seedling morphological and physiological responses to heat treatment duration. Specifically, it was expected that distinct progeny-duration combinations would result in

optimal germination percentage, seedling vigor, and physiological performance, indicating the need for genotype-specific heat treatment regimes rather than a single standardized protocol.

MATERIALS AND METHODS

Experimental site

The experiment was conducted in 2021, and seeds germinated at the Ghana Sumatra Limited. Subsequent nursery work was carried on at the Council for Scientific and Industrial Research-Oil Palm Research Institute (CSIR-OPRI) nursery, located in Kusi within the Denkyemba District of the Eastern Region of Ghana. The area lies between latitudes $06^\circ 02'$ and $06^\circ 05'$ North and longitudes $00^\circ 52'$ and $00^\circ 54'$ West of the Greenwich meridian, with an elevation of 164 m above sea level. The average annual rainfall in this location is 1425 millimeters. Bimodal rainfall, which occurs during two distinct seasons, characterizes the area. The first rainy season begins in April and lasts until July, while the second season begins in September and lasts until the end of October or the middle of November. The dry season occurs after the minor wet season ends and the major wet season begins. Temperatures are generally high and uniform throughout the year. The average monthly temperatures vary from 24 to 30°C (Danso et al. 2020).

Experimental design and treatments

Commercial *dura* × *pisifera* (D × P) hybrid oil palm seeds from four progenies (61, 131, 132, and 136) were obtained from Ghana Sumatra Limited. The experiment was conducted as a 4×4 factorial arrangement in a Randomized Complete Block Design (RCBD) with four replications. The treatment structure comprised four progenies (P: 61, 131, 132, and 136) and four heat treatment durations (D: 55, 60, 65, and 70 days), generating sixteen treatment combinations: P61D55, P61D60, P61D65, P61D70, P131D55, P131D60, P131D65, P131D70, P132D55, P132D60, P132D65, P132D70, P136D55, P136D60, P136D65, and P136D70. This resulted in a total of 64 experimental units (16 treatments × 4 replications). Each experimental unit consisted of 540 seeds placed in a 40 cm × 60 cm polyethylene bag. Seed germination was recorded following emergence, while seedling growth parameters were measured monthly during nursery development. For statistical analysis, monthly measurements for each growth variable were averaged across the observation period to obtain a single mean value per experimental unit. These mean values were then used for analysis, thereby treating the data as cross-sectional rather than longitudinal.

Pre-treatment measurements (Seed viability)

Seed viability was assessed using the tetrazolium chloride (TZ) test on 10 seeds randomly selected from each progeny, following the procedure described by Fondom et al. (2010). The endocarp was carefully removed to expose the endosperm, and embryos were immersed in a 1% (10 g

L⁻¹) aqueous tetrazolium chloride solution and incubated in the dark for 6-8 hours. Embryos exhibiting red or pink staining were considered viable. Percentage viability was calculated according to standard TZ evaluation criteria. Although the viability test was conducted on a relatively small subsample compared with the total number of seeds per experimental unit (540 seeds), it was used as a preliminary quality control measure to confirm high physiological viability of the seed lots prior to germination. Only progenies exhibiting viability above 90% were advanced for germination trials. Given the uniformly high viability observed across progenies, the subsample size was considered adequate for screening purposes; however, this represents a limitation of the study, and larger subsamples would improve precision in future evaluations.

$$\text{Percentage viability} = \frac{\text{Number of viable (stained) seeds}}{\text{Total number of seeds tested}} \times 100$$

Moisture content

Seed moisture content was determined using the oven-drying method at 105°C for 24 h, following the procedure of Brasil (2009). Measurements were based on 10 seeds per experimental unit, and moisture content was calculated as the percentage loss in fresh weight after drying. Only progenies with mean moisture contents exceeding 13% were selected for the experiment. Given the relatively small subsample size, moisture content estimates are subject to greater sampling error and wider confidence limits than would be expected from larger samples. However, the assessment was used strictly as a preliminary screening tool to confirm adequate seed hydration prior to heat treatment. As moisture levels were consistently above the selection threshold across progenies, the potential influence of sampling error on progeny inclusion was minimal. Nonetheless, this represents a limitation of the study, and future investigations would employ larger seed subsamples to improve estimation precision.

$$\text{MC} = \frac{\text{FW} - \text{DW}}{\text{DW}} \times 100$$

Where:

MC: Moisture content

FW: Fresh Weight

DW: Dry Weight

Application of heat-treatment duration

Seeds assigned to different treatments were soaked in clean water for seven days to raise the moisture content above 18%, with the water replaced daily to prevent microbial contamination. After soaking, seeds were surface treated with a fungicide mixture consisting of 100 g Agrithane, 50 g Bendazim, and 50 ml of detergent added to 50 liters of water. The seeds were immersed in the solution for five minutes and then transferred to shaded areas to air-dry for 3-4 hours. Post-soaking, seeds were packed into 40 cm × 60 cm transparent polyethylene bags with an adequate volume of air retained and firmly tied. Bags were placed in a hot room maintained at 41±1°C for durations of 55, 60, 65, or 70 (check) days. Throughout this period, periodic checks were conducted for fungal growth and aeration. Following the completion of heat treatment, seeds

were soaked again for four days (with daily water replacement), retreated with fungicide, dried under shade for 3-4 hours, and then transferred to the germination chamber.

Sorting of germinated seeds

Seeds started sprouting after two weeks, and weekly sorting of sprout seeds was carried out for a period of eight (8) weeks. Seeds were considered germinated when the radicle and plumule emerged from the testa. Germination Percentage (GP) was calculated as the final cumulative germination at the end of the observation period using the formula of Seefeldt (2012):

$$\text{Germination Percentage} = \frac{\text{Number of seeds germinated}}{\text{Total number of seeds tested}} \times 100$$

Nursery establishment

One hundred (100) sprouted seeds of each treatment were randomly planted across the four blocks, with 25 sprouted seeds per block at the Oil Palm Research Institute. Within each block, all 16 treatment combinations (4 progenies × 4 heat durations) were represented, minimizing environmental variation and ensuring valid statistical comparisons. The germinated sprouted nuts were planted under 55% light penetration during the pre-nursery in 5 x 8 black polybags filled with topsoil. The seed nut was planted 4 cm deep with the radicle facing downward and the plumule upward, placed horizontally in a hole made with a stick, then lightly covered and gently firmed to ensure adequate soil contact. Seedlings were transferred from the pre-nursery to the main nursery after 4 months. Before transplanting, vertical holes slightly larger than the pre-nursery bags were made at the center of each maxi polybag (9×11×14 black polybag filled with topsoil) using an auger. One side of the pre-nursery bag was torn, and the seedling, with its soil ball intact, was gently inserted into the hole. Soil was firmed around the root mass to ensure stability, maintaining the same soil level as in the pre-nursery. The surface was then mulched with sawdust.

Data collection

Data collection started when seedlings were five (5) months old, and data were taken on a monthly basis for eight months (5 to 12 months after planting). Ten plants per plot were randomly selected using a simple random sampling and tagged for data collection for each of the growth and physiological parameters studied. These parameters observed are as follows:

Plant Height (PH)

Data on plant height were taken with a tape measure from the soil level in the polybag to the tip of the longest leaf at monthly intervals from 5 to 12 months after planting.

Number of Leaves (NL)

The number of leaves per plant was determined by counting the number of leaves on the randomly selected seedlings on a monthly basis.

Leaf length and width

A nondestructive method was used for the leaf area. The length and the greatest Width of each leaf was measured with a ruler on each of the selected plants sampled per plot.

Butt Circumference (BC)

Butt circumference was measured using a pair of Vernier calipers to determine the diameter at two places on the butt, 0.5 cm from the soil level. Measurements were taken at monthly intervals, and the formula πd determined the circumference; π was taken as 3.14 and d is the average diameter measured.

Chlorophyll Content (CC)

Leaf chlorophyll content was measured using a SPAD-502 Plus chlorophyll meter following standard non-destructive procedures (Uddling et al. 2007; Cerovic et al. 2012). Measurements were taken on fully expanded, intact leaves. Prior to assessment, leaf blades were gently cleaned with distilled water and wiped dry. Each leaf was positioned between the sensor arms of the meter, and three readings were taken at random positions around the midpoint of the leaf blade. The mean of the three readings was used for statistical analysis. As no calibration was performed to convert SPAD values to absolute chlorophyll concentration, chlorophyll content is reported as a relative SPAD index (SPAD units).

Stomatal Conductance (SC)

Stomatal Conductance (SC) was measured on the adaxial surface of fully expanded, sun-exposed leaves using a SC-1 Leaf Porometer (Decagon Devices, Pullman, WA, USA). The SC-1 is an automated, hand-held device that determines stomatal conductance by measuring the rate of water vapor flux from a leaf when clamped between the sensor arms. Measurements were conducted between 11:00 am and 2:00 pm, close to solar noon, to minimize diurnal variation. For each experimental unit, young, intact, green leaves fully exposed to sunlight were randomly selected. Each leaf was carefully positioned within the sensor chamber, and the instrument automatically calculated SC in $\text{mmol m}^{-2} \text{s}^{-1}$. Three readings per leaf were taken at random points near the midpoint of the lamina, and the mean was used for statistical analysis. This protocol provided a standardized, non-destructive assessment of leaf gas exchange, allowing reliable comparison of stomatal activity among treatments (Ling et al. 2011).

Data analysis

Data collected were subjected to Analysis of Variance (ANOVA) using R Statistical Software, version 4.5.1, and treatment means were compared using Tukey's Honestly Significant Difference (HSD) at a 5% level of significance. Prior to analysis, the data were checked for normality and the homogeneity of variances. Data followed a normal distribution, and assumptions of ANOVA were not violated.

RESULTS AND DISCUSSION

Descriptive statistics (Table 2) revealed that Germination Percentage (GP) across all treatments was consistently high, averaging 90.52% (range: 86.99-98.84%, CV 6.26%), indicating that the protocols successfully broke seed dormancy for most progenies and heating durations. GP varied significantly among treatments ($p < 0.05$). Plant Height (PH) also showed significant variation (mean 50.01 cm; range 46.31-57.15 cm; CV 6.04%). In contrast, morphological traits Number of Leaves (NL, mean 9.63), Leaf Length (LL, mean 33.88 cm), Leaf Breadth (LB, mean 9.35 cm), and Butt Circumference (BC, mean 8.68 cm)-displayed non-significant variation ($p > 0.05$) (Table 1), with coefficients of variation below 13%, denoting consistency across treatments. Significantly, physiological parameters such as Chlorophyll Content (CC) and Stomatal Conductance (SC) varied considerably among treatments (CC: mean 49.89 SPAD units, range 45.91-54.31 mg/g, CV 5.66%; SC: mean 15.14 $\text{mmol m}^{-2} \text{s}^{-1}$, range 11.84-20.55 $\text{mmol m}^{-2} \text{s}^{-1}$, CV 13.66%), indicating their impact on seedling photosynthetic capacity and water regulation.

Germination Percentage (GP) exhibited a clear progeny \times heat duration interaction ($P \times D$) (Table 3), indicating that the effect of heating duration depended on the genotype. The highest GP was recorded for progeny 131 at 65 days (98.84%), followed by progeny 136 at 60 days (97.73%), both forming distinct statistical groups ($p < 0.05$, Tukey's HSD). Conversely, progeny 132, at 60 days, showed the lowest germination (82.27%), in a distinct group from most other combinations. Most remaining combinations fell within a common statistical group (denoted "ab"), reflecting generally high germination yet highlighting optimal genotype-duration matches for maximizing seed viability.

Seedling growth exhibited clear progeny \times heat duration ($P \times D$) interactions (Table 4), indicating that responses to heat treatment depended on genotype. Plant Height (PH) was highest in progeny 131 at 60 days (57.15 cm) and lowest in progeny 132 at 70 days (46.31 cm), reflecting patterns observed in germination percentages and highlighting genotype-specific responses to heat duration. In contrast, morphological traits, including the number of leaves, leaf length, leaf breadth, and butt circumference, remained largely stable across treatments, suggesting that seedling structure is less sensitive to heat treatment once germination is achieved.

Physiological traits showed greater variability. Chlorophyll content, measured as SPAD units, was highest in progeny 132 at 65 days (54.31 SPAD units) and lowest in the same progeny at 55 days (45.91 SPAD units). Similarly, stomatal conductance (SC, $\text{mmol m}^{-2} \text{s}^{-1}$) peaked in progeny 132 at 65 days (20.55) and tended to increase with longer heat durations (65-70 days), potentially reflecting enhanced metabolic activity and adaptive physiological responses. These patterns indicate that specific progeny-duration combinations optimize both germination and early seedling physiological performance, whereas morphological traits remain relatively unaffected by heat treatments.

Table 1. Mean squares for oil palm seed germination and seedling growth traits

SV	Df	Mean square							
		GP	PH	NL	LL	LB	BC	CC	SC
R	3	66.13	11.4960	0.02134	0.6613	1.04466	0.62589	6.5670	5.4745
P	3	57.737	68.3752	0.32479	11.9843	0.41552	2.20366	5.0380	8.8240
D	3	34.657	3.1265	0.12341	0.9875	0.85402	1.76540	16.3250	7.5818
P×D	9	118.483*	13.4520*	0.09321ns	2.3335ns	0.41299ns	0.99644ns	29.0747*	36.4271*
Error	45	32.133	9.1140	0.11558	2.6863	0.54366	1.10276	7.9661	4.2756
Total	63								

Note: SV: Sources of variation, R: Replication, P: Progeny, D: Duration, Df: Degree of freedom, GP: Germination Percentage (%), PH: Plant Height (cm), NL: Number of Leaves, LL: Leaf Length (cm), LB: Leaf Breath (cm), BC: Butt Circumference (cm), CC: Chlorophyll Content (SPAD unit), SC: Stomatal Conductance (mmol m⁻² s⁻¹), *: Significant at P<0.05 and ns: Not significant

Table 2. Descriptive statistics of oil palm seed germination and seedling growth traits

Trait	Mean	SE	Min	Max	CV	Sign. level (p<0.05)
GP	90.52	4.01	86.99	98.84	6.26	*
PH	50.01	2.47	46.31	57.15	6.04	*
NL	9.63	0.28	9.27	10.09	3.52	ns
LL	33.88	1.34	32.08	35.86	4.84	ns
LB	9.35	0.60	8.90	10.35	7.88	ns
BC	8.68	0.86	7.86	10.49	12.10	ns
CC	49.89	2.30	45.91	54.31	5.66	*
SC	15.14	1.69	11.84	20.55	13.66	*

Note: *: p<0.05; ns: Not significant, GP: Germination Percentage (%), PH: Plant Height (cm), NL: Number of Leaves, LL: Leaf Length (cm), LB: Leaf Breath (cm), BC: Butt Circumference (cm), CC: Chlorophyll Content (SPAD unit), SC: Stomatal Content (mmol m⁻² s⁻¹), SE: Standard Error, Min: Minimum, Max: Maximum, Sign. Level: Significant Level

Table 3. Mean germination percentage of progenies and heating durations

Progeny(P)	Duration (D) (Days)	Germination Percentage (GP) (%)
61	55	91.58ab
61	60	93.75ab
61	65	85.56ab
61	70	88.94ab
131	55	86.99ab
131	60	92.27ab
131	65	98.84a
131	70	94.86ab
132	55	89.95ab
132	60	82.27b
132	65	95.65ab
132	70	87.41ab
136	55	89.35ab
136	60	97.73a
136	65	88.10ab
136	70	85.05ab

Note: Means within columns with different letters are significantly different by the Tukey's HSD test at 5% probability

Table 4. Mean oil palm seedlings nursery growth parameters of progenies and heating durations

Progeny (P)	Duration (D) (Days)	PH	NL	LL	LB	BC	CC	SC
61	55	51.65ab	9.65a	34.73a	9.46a	9.36a	48.91a	13.69bc
61	60	48.21ab	9.39a	32.49a	8.91a	8.25a	46.88b	18.04abc
61	65	50.25ab	9.72a	34.47a	9.87a	8.06a	48.01ab	15.21abc
61	70	50.38ab	10.10a	33.99a	9.88a	8.23a	54.05c	12.60bc
131	55	50.21ab	9.27a	34.09a	10.35a	7.89a	50.34ab	13.85bc
131	60	57.15a	9.39a	34.84a	9.12a	8.62a	50.33ab	12.93bc
131	65	49.88ab	9.40a	33.19a	9.11a	7.91a	48.70ab	16.58abc
131	70	53.67ab	9.56a	35.86a	9.13a	9.16a	47.44ab	13.17bc
132	55	47.25b	9.97a	32.48a	9.45a	8.48a	45.91b	16.02abc
132	60	46.39b	9.61a	32.77a	8.90a	8.70a	47.49ab	11.84c
132	65	47.69b	9.63a	32.49a	9.06a	8.46a	54.31c	20.55a
132	70	46.31b	9.76a	32.08a	8.98a	8.56a	53.78c	13.03bc
136	55	50.92ab	9.73a	34.36a	9.38a	9.12a	49.76ab	13.31bc
136	60	50.35ab	9.72a	35.17a	9.13a	9.38a	51.43bc	18.52ab
136	65	49.45ab	9.86a	34.03a	9.24a	8.28a	52.72bc	12.21c
136	70	50.46ab	9.68a	35.03a	9.64a	10.49a	48.09ab	20.46a

Note: PH: Plant Height (cm), NL: Number of Leaves, LL: Leaf Length (cm), LB: Leaf Breath (cm), BC: Butt Circumference (cm), CC: Chlorophyll Content (SPAD unit), SC: Stomatal Content (mmol m⁻² s⁻¹). Means within each column with the same letter are not significantly different by the Tukey's HSD test at 5% probability

Discussion

The study demonstrates that oil palm seed germination and early seedling vigor are strongly influenced by the interaction between progeny and heat treatment duration (P×D). Germination Percentage (GP) averaged 90.52 percent, ranging from 82.27 to 98.84 percent, but the highest GP occurred only in specific progeny-duration combinations. Progeny 131 at 65 days recorded 98.84 percent, and progeny 136 at 60 days recorded 97.73 percent, while progeny 132 at 60 days had the lowest GP of 82.27 percent. These results clearly indicate that optimal heat treatment is not uniform across genotypes, highlighting the importance of tailoring dormancy-breaking protocols to specific progenies rather than relying on a single standard treatment. Similar findings have been reported by Beugré et al. (2009), Fondom et al. (2010), and Kerdaffrec and Nordborg (2017), who showed that seed viability and germination responses vary according to genotype due to differences in endocarp structure, embryo sensitivity, and hormonal regulation.

Seedling growth responses also reflected the P×D interaction. Plant height was highest in progeny 131 at 60 days, measuring 57.15 cm, and lowest in progeny 132 at 70 days, measuring 46.31 cm, mirroring germination trends and reinforcing that rapid and synchronous germination contributes to early vigor (Reed et al. 2022). Morphological traits, including number of leaves, leaf length, leaf breadth, and butt circumference, showed minimal variation across progeny-duration combinations, with coefficients of variation below 13 percent. This stability suggests that basic seedling architecture is largely determined by genetic potential and is less responsive to heat treatments once dormancy is broken, a pattern previously observed in nursery trials of oil palm and other perennial crops (Wei et al. 2021).

Physiological traits were more sensitive to P×D interactions. Chlorophyll content measured as SPAD units and stomatal conductance in $\text{mmol m}^{-2} \text{s}^{-1}$ varied significantly among progeny-duration combinations, peaking in progeny 132 at 65 days with values of 54.31 SPAD and $20.55 \text{ mmol m}^{-2} \text{s}^{-1}$. Lower values were observed in other combinations, such as progeny 132 at 55 days, which had a chlorophyll content of 45.91 SPAD. These observations indicate that early seedling metabolic activity and photosynthetic capacity are dependent on the specific progeny-duration pairing, making physiological measurements valuable indicators of treatment effectiveness. The tendency for longer heat durations of 65 to 70 days to increase stomatal conductance in some progenies may reflect enhanced metabolic activity and improved gas exchange under nursery conditions, while excessive heat for less responsive progenies may inhibit germination or early growth, consistent with Hofmann et al. (2025). These physiological sensitivities likely arise from genotypic differences in endocarp permeability to heat and water, which governs oxygen diffusion to the embryo during dormancy release, and varying embryo sensitivity to thermal stress that modulates gibberellin-

abscisic acid balances. Progeny 132 exemplifies decoupled germination and physiological responses, with peak chlorophyll content and stomatal conductance despite low germination rates, suggesting resilient post-germination mesophyll development compensates for delayed radicle emergence (Bradford et al. 2008).

The interaction patterns observed emphasize that heat duration cannot be universally applied across all progenies. Heat treatments of 60 to 65 days were effective for progenies 131 and 136, but other progenies required specific durations to maximize germination and physiological performance. These findings align with studies by Rhebergen et al. (2018) and Soltani et al. (2021), who reported genotype-specific responses to dormancy-breaking protocols in oil palm and other tropical species. The results also reinforce the importance of monitoring physiological traits alongside morphological parameters to identify the most effective progeny-duration combinations (MOFA 2020; Wongvarodom et al. 2024).

This study demonstrates that successful oil palm propagation depends on the careful alignment of genotype and heat treatment duration. Morphological traits remain stable once germination is achieved, indicating that genetic potential dictates plant architecture, whereas physiological traits reflect treatment effectiveness and early seedling health. By integrating genotype-specific heat treatments with monitoring of chlorophyll content and stomatal conductance, nursery managers can optimize germination, vigor, and subsequent crop establishment.

In conclusion, the interaction between progeny and heat treatment duration strongly influenced oil palm seed germination and early seedling growth. Optimal germination occurred at progeny-specific heat durations at $41 \pm 1^\circ\text{C}$, with progeny 61 peaking at 60 days (93.75%), progenies 131 and 132 at 65 days (98.84% and 95.65%), and progeny 136 at 60 days (97.73%). These results confirm that a single heat treatment duration is not optimal for all genotypes. Seedling growth followed similar interaction trends, with the greatest plant height recorded in progeny 131 at 60 days (57.15 cm). Morphological traits showed limited variation across treatments, with coefficients of variation below 13%, indicating structural stability after germination. In contrast, physiological traits were more sensitive to progeny × duration interactions. Chlorophyll content ranged from 45.91 to 54.31 SPAD units, and stomatal conductance varied between 11.84 and $20.55 \text{ mmol m}^{-2} \text{s}^{-1}$, with both parameters peaking in progeny 132 at 65 days. The findings highlight the importance of genotype-specific heat treatment protocols for improving germination uniformity and early seedling performance, while emphasizing the need for further validation under diverse nursery conditions. Future research would validate genotype-specific heat treatment protocols under field conditions, assess long-term growth and yield responses, and explore a wider range of temperature-duration combinations to refine dormancy-breaking strategies for commercial oil palm seed production.

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