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# GAMMA IRRADIATION-INDUCED PHENOTYPIC VARIABILITY IN OIL PALM: INSIGHTS FROM PRINCIPAL COMPONENT AND CLUSTER ANALYSES

## VARIABILITÉ PHÉNOTYPIQUE INDUITE PAR IRRADIATION GAMMA CHEZ LE PALMIER À HUILE: PERSPECTIVES ISSUES DES ANALYSES EN COMPOSANTES PRINCIPALES ET EN CLUSTERS

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## ABSTRACT

Phenotypic variability is a prerequisite for effective selection in mutation breeding programmes. Unfortunately, conventional oil palm (*Elaeis guineensis* Jacq.) breeding programmes often require several years to complete a single selection cycle, thus limiting the rate of genetic gain. Consequently, the development of complementary approaches capable of generating novel genetic variation is essential for accelerating breeding progress and enhancing the efficiency of selection. Therefore, the objective of this study was to assess the extent of phenotypic variability among field-grown gamma-irradiated oil palm genotypes and to identify key traits, divergent groups, and promising genotypes for future oil palm improvement programmes. Germinated Dura × Pisifera (DxP) seeds were irradiated with gamma rays from a cobalt-60 source at doses of 0, 5, 10, 20, 40, 60, 80 and 100 Gy. Seedling responses were assessed three months after planting. Field evaluation was conducted on 112 surviving genotypes derived from the 5, 10 and 20 Gy treatments. Gamma irradiation significantly reduced seedling height and leaf area, with no growth observed at doses of 40 Gy and above. Under field conditions, substantial phenotypic variation was observed among genotypes, with coefficients of variation ranging from 29.16% for plant height to 85.94% for leaf area index. Principal component analysis revealed that the first two principal components explained 85.41% of the total variation, with canopy-related traits contributing most strongly to genotype differentiation. Hierarchical cluster analysis grouped the genotypes into three distinct clusters. Cluster II exhibited superior performance for all

vegetative growth traits, indicating enhanced canopy development and biomass accumulation. The combined PCA-cluster analysis further confirmed the superiority of this cluster and revealed considerable divergence among genotype groups. The results demonstrate that gamma irradiation effectively generated useful phenotypic variability in oil palm and identified promising genotypes for future selection and breeding programmes.

*Key Words*: *Elaeis guineensis,* mutation breeding, phenotypic variability

## RÉSUMÉ

La variabilité phénotypique est une condition préalable à une sélection efficace dans les programmes de sélection par mutation. Malheureusement, les programmes conventionnels d'amélioration du palmier à huile (*Elaeis guineensis* Jacq.) nécessitent souvent plusieurs années pour achever un seul cycle de sélection, limitant ainsi le taux de gain génétique. Par conséquent, le développement d'approches complémentaires capables de générer une nouvelle variation génétique est essentiel pour accélérer les progrès de sélection et améliorer l'efficacité de cette dernière. L'objectif de cette étude était donc d'évaluer l'étendue de la variabilité phénotypique parmi des génotypes de palmier à huile irradiés aux rayons gamma et cultivés en plein champ, et d'identifier les caractères clés, les groupes divergents ainsi que les génotypes prometteurs pour les futurs programmes d'amélioration du palmier à huile. Des graines germées de Dura × Pisifera (DxP) ont été irradiées avec des rayons gamma provenant d'une source de cobalt-60 à des doses de 0, 5, 10, 20, 40, 60, 80 et 100 Gy. Les réponses des plantules ont été évaluées trois mois après la plantation. L'évaluation au champ a été menée sur 112 génotypes survivants issus des traitements à 5, 10 et 20 Gy. L'irradiation gamma a significativement réduit la hauteur des plantules et la surface foliaire, aucun développement n'ayant été observé à des doses de 40 Gy et plus. En conditions de plein champ, une variation phénotypique substantielle a été observée entre les génotypes, avec des coefficients de variation allant de 29,16 % pour la hauteur de la plante à 85,94 % pour l'indice de surface foliaire. L'analyse en composantes principales a révélé que les deux premières composantes principales expliquaient 85,41 % de la variation totale, les caractères liés à la canopée contribuant le plus fortement à la différenciation des génotypes. L'analyse hiérarchique de clusters a regroupé les génotypes en trois clusters distincts. Le groupe II a affiché des performances supérieures pour tous les caractères de croissance végétative, indiquant un développement accru de la canopée et une accumulation de biomasse. L'analyse combinée ACP-cluster a confirmé la supériorité de ce groupe et a révélé une divergence considérable entre les groupes de génotypes. Ces résultats démontrent que l'irradiation gamma a généré efficacement une variabilité phénotypique utile chez le palmier à huile et a permis d'identifier des génotypes prometteurs pour les futurs programmes de sélection et d'amélioration.

*Mots Clés : Elaeis guineensis*, sélection par mutation, variabilité phénotypique

## INTRODUCTION

Oil palm (*Elaeis guineensis* Jacq.) is the most productive oil-bearing crop in the world, accounting for more than one-third of global vegetable oil production from less than 10% of the total area devoted to oil crops (Corley and Tinker, 2016). The crop plays a critical role in food security, industrial development, and income generation in many tropical countries. In West Africa, particularly Ghana, oil palm is an important economic crop cultivated by both smallholder farmers and large-scale plantations, contributing significantly to employment, rural livelihoods, and foreign exchange earnings (Murphy, 2019). The increasing demand for palm oil for food, cosmetic, pharmaceutical, and biofuel industries, has intensified the need for the development of improved planting materials

with higher productivity and better adaptation to changing environmental conditions.

Despite considerable progress in oil palm breeding, genetic improvement remains constrained by the crop's perennial nature, long generation interval, large plant size, and relatively narrow genetic base (Singh *et al*., 2013; Barcelos *et al*., 2015). Conventional breeding programmes often require several years to complete a single selection cycle, limiting the rate of genetic gain. Consequently, the development of complementary approaches capable of generating novel genetic variation is essential for accelerating breeding progress and enhancing the efficiency of selection.

Mutation breeding has emerged as an important tool for broadening genetic variability and creating new allelic combinations that may not be readily available in natural populations. Among the various mutagenic agents, gamma irradiation remains one of the most widely used and effective physical mutagens because of its ability to induce heritable genetic changes ranging from point mutations to chromosomal rearrangements (Mba *et al*., 2010). The successful application of gamma irradiation in several crop species has resulted in the development of improved varieties with enhanced yield, stress tolerance, and agronomic performance (Ahloowalia *et al*., 2004; Konan *et al*., 2019; Saibari *et al*., 2023; Ud-Din *et al*., 2025). In oil palm, induced mutagenesis offers an opportunity to generate novel variation that can complement conventional breeding efforts and expand the genetic base available for selection.

The effectiveness of mutation breeding largely depends on the extent of variability generated and the ability to identify superior genotypes from mutant populations. Phenotypic traits such as leaf area, plant height, rachis length, frond production, and canopy architecture are particularly important because they influence light interception, photosynthetic efficiency, biomass accumulation, and ultimately yield potential (Corley and Tinker, 2016; Okoye *et al*., 2016). The evaluation of such traits provides valuable information for identifying promising genotypes and understanding the nature of variability induced by mutagenic treatments.

Multivariate statistical techniques have become indispensable tools for the analysis of complex datasets involving multiple correlated traits. Principal component analysis (PCA) enables the identification of traits that contribute most to overall variation, while cluster analysis facilitates the classification of genotypes into groups based on phenotypic similarity (Mohammadi and Prasanna, 2003; Cruz *et al*., 2012). The combined application of these methods has proved to be effective for characterising genetic diversity, identifying superior genotypes, and selecting divergent parents for breeding programmes in several crop species, including oil palm (Gan *et a*l., 2021; Fadila *et al*., 2024).

Although gamma irradiation has been used to induce variability in oil palm, most studies have focused on seedling responses and early growth stages, with limited information available on the long-term field performance of irradiated populations. Moreover, there is limited documentation on the use of multivariate approaches to characterise phenotypic diversity in gamma-irradiated oil palm populations under Ghanaian conditions. Understanding the extent and structure of induced variability is essential for the effective utilisation of mutant populations in breeding programmes.

We hypothesised that gamma irradiation would generate sufficient phenotypic variation among oil palm genotypes to permit effective discrimination and identification of superior mutant-derived materials using multivariate statistical approaches. The objective of this study was to assess the extent of phenotypic variability among field-grown gamma-irradiated oil palm genotypes and to identify key traits, divergent groups, and promising genotypes for future oil palm improvement programmes.

## MATERIALS AND METHODS

**Plant materials.** Germinated oil palm seeds of the Dura x Pisifera (DxP) a commercial cultivar, with high homozygosity for vegetative traits, with both emerged plumules and radicles, were obtained from the breeding programme of the CSIR–Oil Palm Research Institute (CSIR-OPRI), Kade, Ghana.

**Study site.** The field experiment was conducted at the experimental station of the CSIR–Oil Palm Research Institute (CSIR-OPRI), Kusi, in the Denkyembour District of the Eastern Region of Ghana. The site is located between latitude 06°022 –06°052 N and longitude 00°522-00°542 W at an altitude of approximately 164 m above sea level. The area experiences a bimodal rainfall pattern with an average annual rainfall of about 1,425 mm. The major rainy season occurs from April to July, while the minor rainy season extends from September to November. Mean annual temperatures range from 24 to 32 °C with relative humidity generally exceeding 75%, providing favourable conditions for oil palm cultivation. The soils are typically classified as Forest Oxysols and Ochrosol-Oxysol intergrades.

**Gamma irradiation.** Gamma irradiation was carried out following Mba *et al*. (2010) and Tshilenge-Lukanda *et al.* (2012). Germinated seeds were exposed to gamma rays from a cobalt-60 (^60Co) source at the Austrian Institute of Technology, Seibersdorf, Austria, at a dose rate of 7.41 Gy $min^{-1}$. Eight doses were initially applied: 0, 5, 10, 20, 40, 60, 80, and 100 Gy.

**Seedling evaluation.** Irradiated seeds were planted in seedling trays containing sterilised peat and sand medium and maintained under greenhouse conditions (22-35°C). The experiment was arranged in a complete randomised design, with four replications. Data were collected 3 months after planting on seedling height and leaf area using five seedlings per replicate. Seedling height was measured from soil surface to the tip of the longest leaf and leaf area was estimated non-destructively according to Corley (1976) using:

$$LA = 0.57 (n \times l \times w)$$

Where:

LA = leaf area ($cm^2$), 0.57 = correction factor, n = number of leaflets, l = mean leaflet length (cm), and w = mean leaflet width (cm).

**Field establishment and vegetative measurements.** Three months after pre-nursery evaluation at the International Atomic Energy Agency Seiberdorf laboratories, Vienna, seedlings were transported to Ghana and maintained in the nursery for approximately one year before field establishment in July 2017 at the CSIR-OPRI experimental station.

During transportation, all control (0 Gy) seedlings were lost; and were therefore excluded from the field trial. Based on nursery survival, only the 5, 10, and 20 Gy treatments were advanced. The trial was laid out in unreplicated blocks with a spacing of 9 m x 9 m between each palm of comprising 53 genotypes for 5gy, 41 for 10gy and 18 for 20gy treatments. Because the objective was characterisation of mutant-derived genotypes rather than treatment comparison, individual palms were considered experimental units for multivariate analysis.

Vegetative measurements were taken annually in 2022 and 2023 on all palms in the trial (five years after planting), and the two-year means were used for analysis. Traits measured included leaf area (LA, $m^2$), total leaf area (TLA, $m^2$), leaf area index (LAI), frond dry weight (FDW, kg), total fronds (TF), rachis length (RACH, m), plant height (HT, m), canopy radius (R, m), and area-to-spread ratio (A/S). Leaf area was estimated from leaflet measurements using standard oil palm procedures, while total leaf area was calculated

as the product of leaf area and total frond number. Leaf area index was determined as the ratio of total leaf area to the ground area occupied by the palm. Frond dry weight was estimated from representative fronds using established allometric relationships. Total fronds were obtained by counting all functional fronds present on each palm.

Rachis length was measured from the base of the frond to the terminal leaflet. Plant height was measured from ground level to the base of frond 41. Canopy radius was measured as the horizontal distance from the centre of the palm stem to the tip of the longest frond and used as an indicator of canopy spread. The area-to-spread ratio (A/S) was calculated as the ratio of total leaf area to canopy spread and was used as an indicator of canopy density and efficiency of canopy space utilisation. Standard procedures described by Corley (1976) and Corley and Tinker (2016) were followed for all measurements.

**Statistical analysis.** Seedling evaluation data was analysed using ANOVA under the complete randomised design using Genstat 23rd Edition (VSN International, 2020) GenStat, with treatment means separated by the LSD test at the 5% level. Descriptive statistics, including mean, standard deviation, coefficient of variation (CV), minimum, maximum, and range, were computed for all vegetative growth traits to assess the extent of phenotypic variability among genotypes. Principal component analysis (PCA) was performed using standardised data (mean = 0, standard deviation = 1) to identify the major sources of variation and the traits contributing most to genotype differentiation. The first two principal components were retained and interpreted because they collectively explained 85.41% of the total variation and provided a meaningful graphical representation of genotype relationships.

Hierarchical cluster analysis was conducted using Euclidean distance as the dissimilarity measure and Ward's minimum variance method for genotype grouping. The resulting dendrogram was used to classify genotypes into clusters based on their phenotypic similarity.

All statistical analyses were performed using R software version 4.5.0 (R Core Team, 2025). Descriptive statistics were computed using the psych package (Revelle, 2024), principal component analysis was conducted using the FactoMineR package (Lê *et al*., 2008), and graphical visualisation of PCA results was generated using factoextra (Kassambara and Mundt, 2020). Hierarchical clustering and dendrogram construction were performed using the STATS package, while data manipulation and visualisation were supported by functions from the tidyverse package (Wickham *et al*., 2019).

## RESULTS AND DISCUSSION

**Seedling growth and development.** Gamma irradiation significantly ($P<0.05$) affected seedling growth and leaf development of oil palm at three months after planting (Table 1; Fig. 1). Seedling height and leaf area decreased progressively with increasing radiation dose, indicating a clear dose-dependent response. The control treatment recorded the highest seedling height ($14.99 \pm 0.55$ cm) and leaf area ($26.97 \pm 3.72$ cm²), whereas seedlings exposed to 20 Gy exhibited the lowest values of $1.73 \pm 0.53$ cm and $0.56 \pm 0.18$ cm², respectively. These reductions correspond to decreases of approximately 88.5% in seedling height and 97.9% in leaf area relative to the control.

The marked reduction in growth observed at higher irradiation doses may be attributed to radiation-induced damage to cellular structures, chromosomes and DNA molecules, resulting in impaired cell division and reduced meristematic activity. Similar reductions in seedling vigour following gamma irradiation; have been reported in oil palm and other crop species (Tshilenge-Lukanda *et al*., 2012; Darkwah *et al*., 2019). The visual observations presented in Figure 1 further confirm the

TABLE 1. Means and standard deviations for oil palm seedling height and leaf area 3 months after Gamma Irradiation

| Dose (Gy) | Seedling height (cm) | Leaf area (cm²) |
|---|---|---|
| 0 | 14.99 ± 0.55a | 26.97 ± 3.72a |
| 5 | 12.57 ± 0.56b | 15.27 ± 2.75b |
| 10 | 10.65 ± 0.50c | 7.32 ± 2.24c |
| 20 | 1.73 ± 0.53d | 0.56 ± 0.18d |
| 40 | 0 | 0 |
| 60 | 0 | 0 |
| 80 | 0 | 0 |
| 100 | 0 | 0 |

Means followed by different letters within a column differ significantly at $P<0.05$. * 0 indicates no growth

Figure 1. Seedling development after gamma ray irradiation of germinated seed of oil palm. The picture shows seedling and leaf area decreasing progressively with increasing dose (from left to right: 0, 5, 10, 20, 40, 60, 80 and 100 Gy) three months after planting.

inhibitory effects of increasing irradiation doses on seedling growth.

The relatively moderate reductions observed at 5 and 10 Gy suggest that these doses may be suitable for mutation induction because they provide opportunities for generating genetic variability; while maintaining acceptable seedling survival and growth. Such intermediate doses are often considered optimal in mutation breeding programmes because they balance mutation frequency with biological damage (Mba *et al*., 2010).

**Phenotypic variability.** Considerable phenotypic variation was observed among the 112 gamma-irradiated oil palm genotypes for all vegetative growth traits evaluated (Table 2). The coefficients of variation (CV) ranged from 29.16% for plant height to 85.94% for leaf area index (LAI), indicating a high level of diversity within the population. Traits associated with canopy development, particularly LAI, total leaf area (TLA), and area-to-spread ratio (A/S), exhibited the greatest variability; suggesting that gamma

TABLE 2. Phenotypic variability and descriptive statistics of vegetative growth traits among gamma-irradiated oil palm genotypes

| Trait | Mean | SD | Minimum | Maximum | CV (%) |
|---|---|---|---|---|---|
| LA (m) | 1.64 | 0.86 | 0.16 | 3.58 | 52.30 |
| TLA ($m^2$) | 33.49 | 25.37 | 0.36 | 89.50 | 75.74 |
| LAI | 0.34 | 0.29 | 0.00 | 1.13 | 85.94 |
| FDW (kg) | 0.67 | 0.23 | 0.09 | 1.29 | 34.37 |
| Total Fronds | 18.45 | 6.64 | 1.00 | 25.00 | 35.98 |
| Rachis Length (m) | 2.04 | 0.64 | 0.65 | 3.57 | 31.55 |
| Height (m) | 11.24 | 3.28 | 5.00 | 18.00 | 29.16 |
| R(as) (m) | 2.07 | 0.66 | 0.78 | 3.50 | 31.72 |
| A/S ($m^2$) | 14.78 | 8.46 | 1.19 | 38.47 | 57.22 |

irradiation effectively generated a wide range of phenotypic responses among the genotypes. Leaf area index recorded the highest coefficient of variation (85.94%), followed by total leaf area (75.74%) and A/S ratio (57.22%). Such high levels of variation are desirable in mutation breeding because they increase the probability of identifying superior genotypes with desirable agronomic characteristics. Similar increases in phenotypic diversity following induced mutagenesis have been reported in oil palm and other crop species, where gamma irradiation broadened the range of variation available for selection (Mba *et al.,* 2010; Darkwah *et al*., 2019; Ud-Din *et al*., 2025).

The mean plant height was 11.24 m, ranging from 5.00 to 18.00 m; while total frond production averaged 18.45 fronds per palm and rachis length averaged 2.04 m. The moderate coefficients of variation observed for these traits (29-36%) indicate appreciable differences among genotypes and suggest that both genetic and environmental factors contributed to the observed variation.

The high variability observed in canopy-related traits is particularly important because these characteristics influence light interception, photosynthetic efficiency, and biomass accumulation;which are closely associated with palm growth and productivity (Corley and Tinker, 2016). Greater leaf area and canopy development enhance the capacity of palms to intercept solar radiation, thereby increasing assimilate production and potentially improving future bunch yield (Woittiez *et al*., 2017). Recent studies have similarly identified canopy architecture and vegetative growth traits as key determinants of diversity and selection potential in oil palm populations (Gan *et al*., 2021; Fadila *et al*., 2024).

Overall, the broad trait ranges and high coefficients of variation observed in this study demonstrate the effectiveness of gamma irradiation in generating phenotypic diversity in oil palm. The variability generated provides a valuable resource for identifying superior genotypes and supports the use of induced mutagenesis as a complementary approach for broadening the genetic base of oil palm breeding programmes.

**Principal component analysis.** Outputs from Principal component analysis (PCA) are presented in Tables 3 and 4; Figure 2. The first two principal components explained 85.41% of the total variation (Table 3), with PC1 accounting for 80.15% and PC2 for 5.26%, indicating that the measured traits effectively captured the phenotypic diversity present within the population. The large contribution of PC1 suggests that differences in vegetative growth and canopy development were the primary factors responsible for genotype differentiation.

TABLE 3. Phenotypic diversity and multivariate analysis of irradiated *Dura* × *Pisifera* (DxP) oil palm genotypes

| Principal component | Eigenvalue | Variance explained (%) | Cumulative variance (%) |
|---|---|---|---|
| PC1 | 7.21 | 80.15 | 80.15 |
| PC2 | 0.47 | 5.26 | 85.41 |
| PC3 | 0.44 | 4.92 | 90.34 |
| PC4 | 0.29 | 3.25 | 93.59 |
| PC5 | 0.22 | 2.40 | 95.99 |

Eigenvalues calculated from standardized variables (9 traits)

TABLE 4. Principal component loadings for vegetative growth traits

| Trait | PC1 | PC2 |
|---|---|---|
| LA (m) | 0.358 | 0.203 |
| TLA (m²) | 0.351 | 0.055 |
| LAI | 0.322 | 0.361 |
| FDW (kg) | 0.292 | -0.708 |
| Total Fronds | 0.322 | -0.408 |
| Rachis Length (m) | 0.329 | 0.382 |
| Height (m) | 0.329 | 0.087 |
| R(as) (m) | 0.346 | -0.067 |
| A/S (m²) | 0.346 | -0.005 |

Traits associated with canopy development, including leaf area, total leaf area, leaf area index, plant height, rachis length, canopy radius, and area-to-spread ratio, exhibited strong positive loadings on PC1; indicating their importance in discriminating among genotypes (Table 4). Similar findings have been reported in oil palm germplasm studies, where vegetative and canopy-related traits were identified as major contributors to genetic diversity and population structure (Arias *et al*., 2015; Gan *et al*., 2021; Fadila *et al*., 2024). These traits are closely linked to palm vigour and overall growth performance and, therefore, provide useful criteria for genotype evaluation and selection.

The strong association among canopy-related traits suggests that they are influenced by common physiological processes related to light interception, photosynthetic efficiency and biomass production. Larger leaf area and improved canopy architecture enhance the ability of palms to capture solar radiation, resulting in increased assimilate production and vegetative growth (Corley and Tinker, 2016). Similar relationships among canopy traits have been reported in oil palm breeding populations, where increased canopy development was associated with improved biomass accumulation and field performance (Singh *et al*., 2020). Recent studies have also emphasised the importance of canopy architecture in the development of compact and high-yielding oil palm varieties suitable for intensive planting systems (Samsudin *et al*., 2025).

Although PC2 explained a relatively small proportion of the total variation, it contributed to the separation of genotypes based mainly on frond dry weight, frond production and rachis length. Although the eigenvalue of PC2

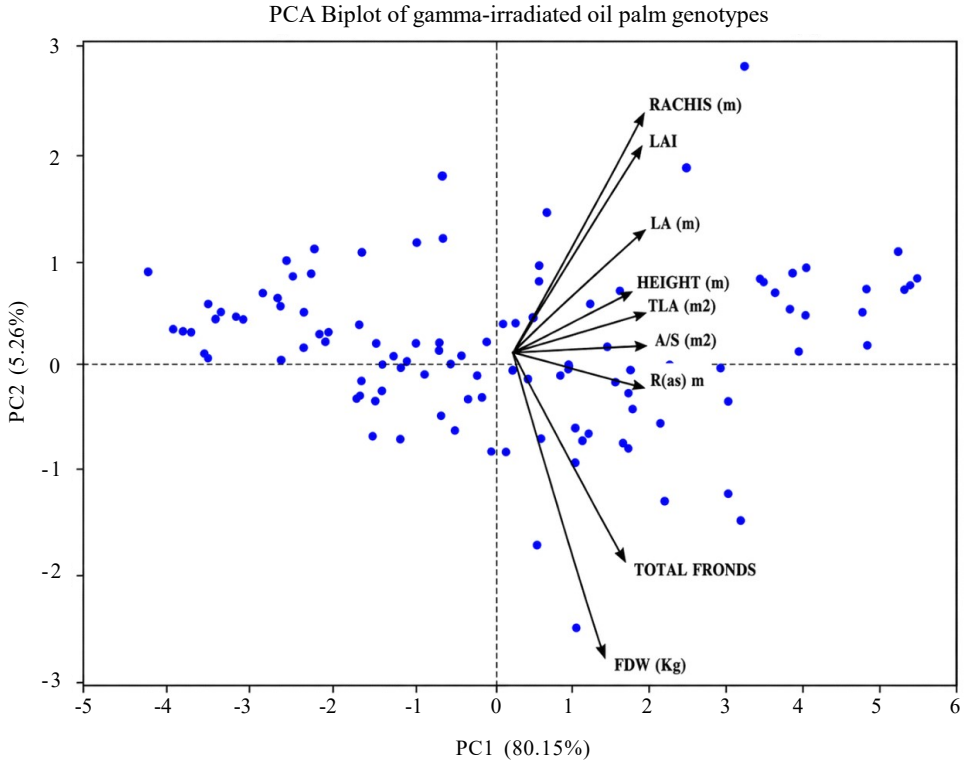


Figure 2. Principal component biplot showing the distribution of gamma-irradiated oil palm (*Elaeis guineensis* Jacq.) genotypes and the contribution of vegetative growth traits to the first two principal components.

was less than one, it was retained because together with PC1 it accounted for 85.41% of the total variation and provided a meaningful two-dimensional representation of genotype relationships. These traits may represent secondary sources of variation associated with biomass accumulation and growth efficiency. Together, the first two principal components provided a comprehensive summary of the phenotypic diversity within the irradiated population and highlighted the importance of vegetative growth traits in the identification of superior genotypes for oil palm improvement programmes. The PCA biplot (Fig. 2) illustrates the distribution of genotypes and the contribution of vegetative growth traits to the first two principal components

**Cluster analysis and genotype grouping.** Hierarchical cluster analysis classified the 112 gamma-irradiated oil palm genotypes into three distinct clusters (Fig. 3), indicating the presence of substantial phenotypic diversity within the population. The clustering pattern was consistent with the PCA results, confirming the effectiveness of the multivariate analyses in discriminating among genotypes based on vegetative growth characteristics.

Cluster II was identified as the most vigorous group, exhibiting the highest mean values for all measured traits, including leaf area, total leaf area, leaf area index, frond dry weight, total frond production, rachis length and plant height. The superior performance of genotypes within this cluster reflects enhanced canopy development and biomass accumulation, traits that are closely associated with improved growth and productivity in oil palm (Corley and Tinker, 2016). The concentration of high-performing genotypes within this cluster suggests that gamma irradiation successfully generated favourable

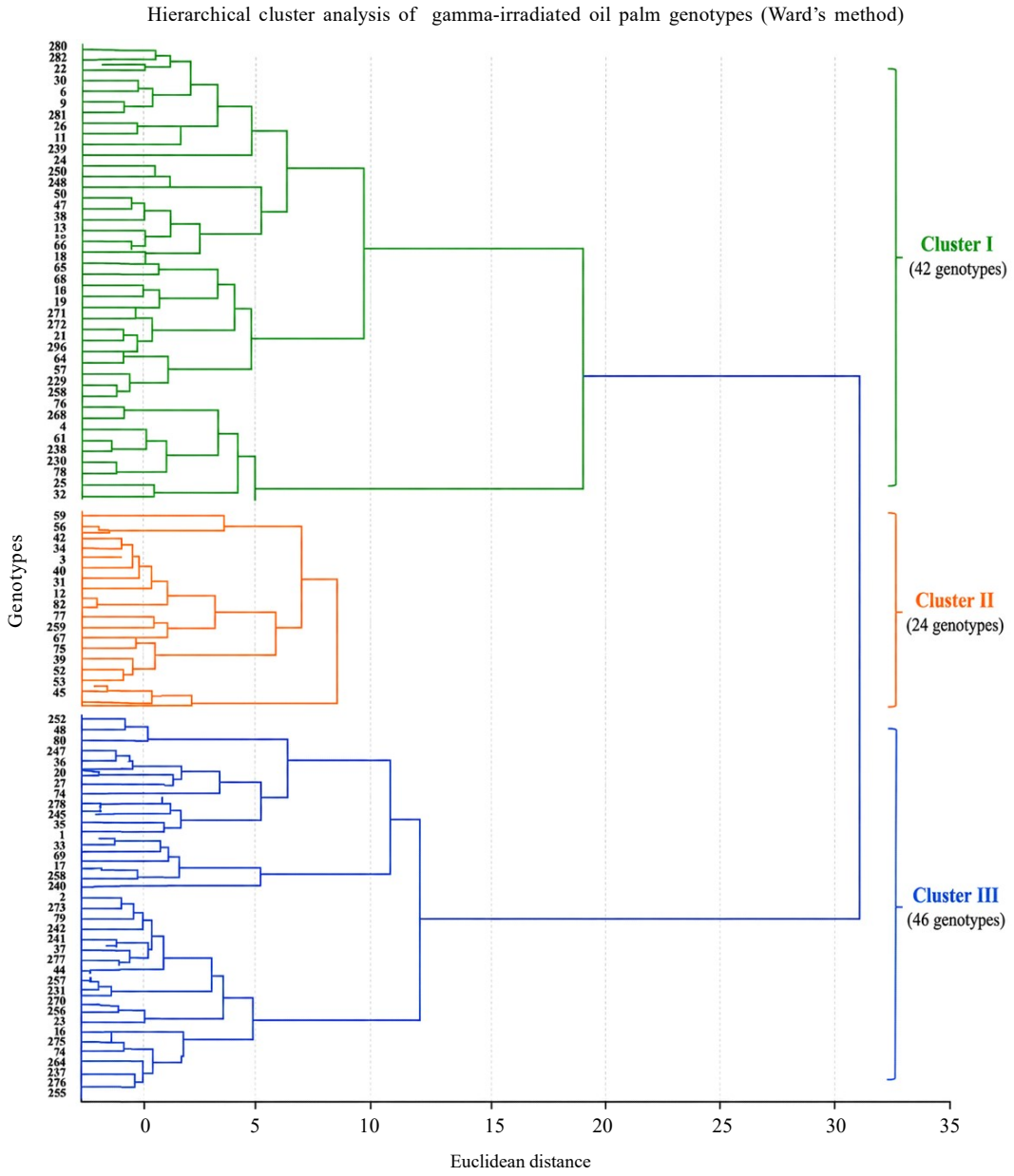


Figure 3. Hierarchical dendrogram of gamma-irradiated oil palm genotypes generated using Ward's clustering method based on standardised vegetative growth traits.

genetic variation that may be exploited in future breeding programmes. Similar findings have been reported in mutation breeding studies where induced mutagenesis resulted in the identification of superior genotypes with enhanced vegetative vigour and agronomic performance (Mba, 2013; Saibari *et al*., 2023).

In contrast, Cluster I comprised genotypes with comparatively lower values for most vegetative traits, indicating reduced growth vigour and canopy development. The poor performance of these genotypes may be attributed to unfavourable mutations or residual physiological effects associated with irradiation. Nevertheless, the marked divergence between Cluster I and the superior Cluster II highlights the broad range of variability generated within the population. Such divergence is valuable in breeding programmes because genetically distinct parents often provide greater opportunities for recombination and selection gain in subsequent generations (Acquaah, 2012).

Cluster III exhibited intermediate values for most traits and represented a group of moderately vigorous genotypes. Although these accessions did not perform as well as those in Cluster II, they may possess unique trait combinations that could be useful for specific breeding objectives or adaptation to different production environments. Similar intermediate clusters have been reported in oil palm diversity studies and are often considered important reservoirs of genetic variation for long-term improvement programmes (Gan *et al*., 2021; Fadila *et al*., 2024).

Overall, the clustering results demonstrate that gamma irradiation effectively generated phenotypic divergence among oil palm genotypes and facilitated the identification of distinct groups with varying levels of vegetative performance. The mean performance of the three clusters is presented in Table 5. The superior genotypes in Cluster II represent promising candidates for further evaluation and selection, while the divergence among clusters provides opportunities for the development of improved breeding populations through strategic hybridisation

**Combined PCA-cluster analysis.** The combined PCA-cluster plot (Fig. 4) provided a clearer understanding of the relationships among the gamma-irradiated oil palm genotypes and their association with key vegetative growth traits

Genotypes belonging to Cluster II were predominantly positioned on the positive side of PC1 and were closely associated with favourable characteristics such as larger leaf area, greater total leaf area, higher frond production, and increased biomass accumulation. This distribution indicates that genotypes within this cluster possess superior

TABLE 5. Performance of vegetative growth traits within clusters identified by Ward's hierarchical cluster analysis

| Trait | Cluster I = 42 | Cluster II = 24 | Cluster III = 46 |
|---|---|---|---|
| LA (m) | 0.80 | 2.89 | 1.77 |
| TLA ($m^2$) | 8.62 | 69.64 | 38.03 |
| LAI | 0.12 | 0.76 | 0.33 |
| FDW (kg) | 0.49 | 0.93 | 0.72 |
| Total fronds | 11.67 | 25.00 | 21.30 |
| Rachis length (m) | 1.45 | 2.84 | 2.18 |
| Height (m) | 8.48 | 16.17 | 11.30 |
| Radius (m) | 1.42 | 2.83 | 2.27 |
| A/S ($m^2$) | 6.97 | 25.65 | 16.45 |

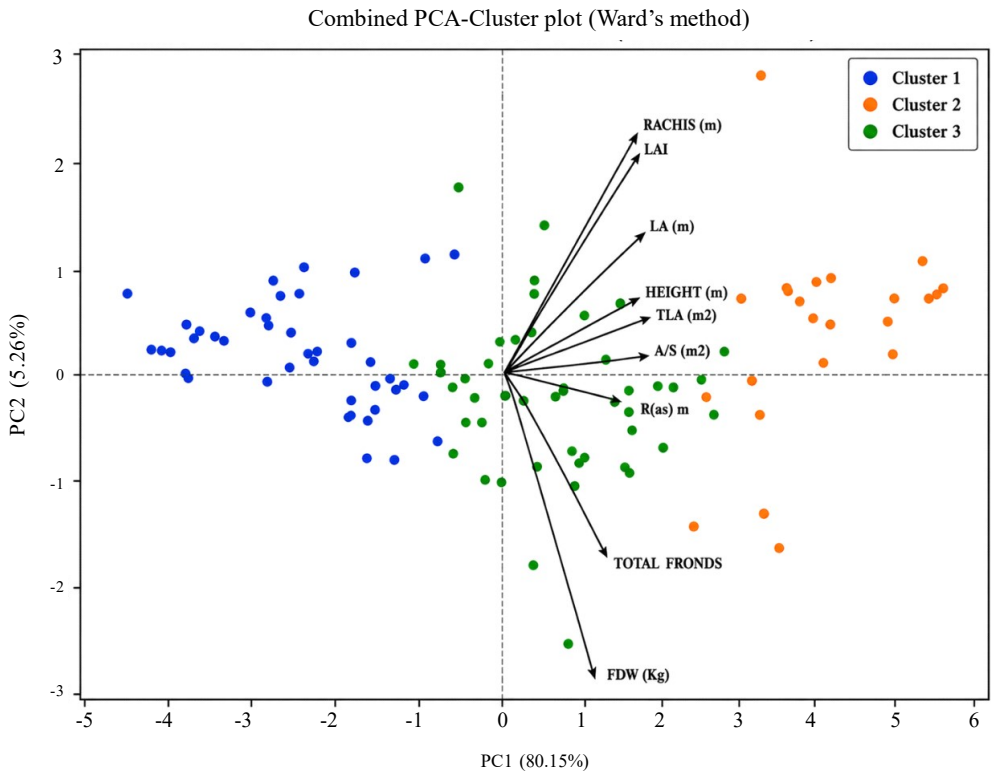


Figure 4. Combined PCA–cluster plot of 112 gamma-irradiated oil palm genotypes showing cluster membership and trait associations based on the first two principal components.

vegetative vigour and growth potential. Similar relationships between positive PCA scores and desirable agronomic traits have been reported in oil palm diversity studies, where superior genotypes were consistently associated with favourable growth and yield-related characteristics (Gan *et al*., 2021; MPOB, 2024).

The distinct separation between Clusters I and II further highlights the substantial phenotypic diversity generated through gamma irradiation. Such divergence demonstrates the effectiveness of induced mutagenesis in creating novel variation that can be exploited for crop improvement. Recent studies have emphasised the role of gamma irradiation in broadening the genetic base of breeding populations and facilitating the development of improved genotypes with desirable agronomic attributes (Saibari *et al*., 2023; Bharath *et al*., 2024; Ud-Din *et al*., 2025).

The superior performance of Cluster II suggests that genotypes within this group represent valuable breeding materials and should be prioritised for further evaluation and selection. In addition, the pronounced divergence between Clusters I and II provides opportunities for strategic hybridisation, as crosses between genetically distinct groups are more likely to generate greater recombination and wider segregation in subsequent generations. Overall, the integration of PCA and cluster analysis proved effective in identifying elite genotypes, elucidating patterns of diversity, and providing a robust basis for the selection and management of genetic resources in oil palm mutation breeding programmes.

Based on these findings, genotypes from Cluster II should be advanced for multi-location testing and long-term yield evaluation

to determine their agronomic potential and stability. Furthermore, strategic hybridisation between superior genotypes from Cluster II and divergent genotypes from other clusters is recommended to maximise genetic recombination and broaden the breeding population. Future studies should also incorporate molecular characterisation to complement phenotypic selection and facilitate the identification of elite mutant lines for oil palm breeding in Ghana and other oil palm-growing regions.

## CONCLUSION

Gamma irradiation effectively generated substantial phenotypic variability among oil palm (*Elaeis guineensis* Jacq.) genotypes; demonstrating its potential as a valuable tool for broadening the genetic base of breeding populations. While high irradiation doses (40–100 Gy) severely inhibited seedling growth and survival, the 5, 10 and 20 Gy treatments produced sufficient variation for effective selection. The high coefficients of variation observed for canopy-related traits, particularly leaf area index, total leaf area and area-to-spread ratio, indicate the successful induction of useful phenotypic diversity.

Principal component and cluster analyses revealed that vegetative vigour and canopy development traits were the major sources of variation among genotypes. The analyses further identified three distinct genotype groups, with Cluster II exhibiting superior performance for leaf area, total leaf area, frond production, biomass accumulation, and plant height. These genotypes represent promising candidates for further evaluation and selection in oil palm improvement programmes.

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