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Principal component analysis and agglomerative clustering of morphological variations in two different species of oil palm (*Elaeis oleifera* and *Elaeis guineensis*)

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Abstract
This study investigated morphological diversity in 40 oil palms comprising *Elaeis oleifera* (23 genotypes) and *Elaeis guineensis* (17 genotypes) using 14 morphological traits. Principal Component Analysis (PCA) revealed that structural vigour traits - palm height, girth, rachis length, and leaflet dimensions - dominated variation (PC1, 50.64%), while leaf production (PC2, 13.53%), growth-reproduction trade-offs (PC3, 9.75%), and leaflet number versus reproductive allocation (PC4, 7.45%) accounted for additional variability. Agglomerative Hierarchical Clustering (AHC) partitioned genotypes into three clusters: two dominated by E. oleifera, characterized by taller palms, broader canopies, and lower reproductive ratios, and one dominated by E. guineensis, marked by shorter palms and higher reproductive allocation. The analyses highlight inter- and intra-specific variation, revealing trade-offs between vegetative robustness and reproductive efficiency. These findings underscore the value of PCA and clustering in identifying genotypes with desirable trait combinations, supporting breeding strategies aimed at combining structural vigour with yield efficiency in oil palm improvement programs.

Keywords: Oil palm, *Elaeis guineensis, Elaeis oleifera*, morphological diversity, Principal Component Analysis (PCA), Agglomerative Hierarchical Clustering (AHC), Genetic improvement

Introduction
Oil palm (*Elaeis* sp.) is a perennial diploid (2n=32) monocotyledon belonging to the family Arecaceae and sub-family Cocosoideae (Cronquist, 1981) [11]. Oil Palm has three accepted species *E. guineensis* (The African Oil palm), *E. oleifera* (The American Oil palm) and *E. odora*. Among these only *E. guineensis* and *E. oleifera* are commercially cultivated. At present the palm exists in a wild, semi-wild and cultivated state in three main areas of the equatorial tropics: Africa, South-east Asia and South & Central America, with Africa or South-American being probable center of origin of the palm (Corley and Tinker, 2016) [10].

As a crop, oil palm has gained wider acceptance than other oleaginous crops of the tropical belt, being by far the highest oil yielder per unit area (Sundram *et al.*, 2003; Corley & Tinker, 2016) [28, 10]. Unlike traditional oilseeds, the fruit mesocarp of oil palm contains a large reserve of storage lipids yielding palm oil, while the nut of the fruit provides palm kernel oil (Yusoff, 2024; Basiron, 2007) [31, 6]. The lipid composition, fatty acid profile, and vitamin content (A and E) of oil palm confer on the crop a distinct nutritional and commercial value (Sundram *et al.*, 2003; Ng *et al.*, 2012) [28, 20]. Increasing attention is also being given to the use of palm oil as biodiesel, owing to its superior yield compared to other crops (Basiron, 2007; Ong *et al.*, 2011) [6, 21]. Consequently, oil palm has been recently introduced in India as an irrigated crop, and systematic breeding programs have been initiated for its genetic improvement (Corley & Tinker, 2016) [10].

But, due to its allogamous and highly heterozygous nature, each oil palm is considered a distinct genotype, resulting in a relatively narrow genetic base (Rival & Parveez, 2010; Hayati *et al.*, 2004) [25, 13]. For a successful breeding programme, the assessment of genetic diversity is essential (Bakoumé *et al.*, 2015; Cochard *et al.*, 2009) [3, 9]. Therefore, an attempt has been made to study morphological variations in 40 oil palms [23 *oleifera* (*Elaeis oleifera* HBK. cortes) and 17 *guineensis* (*Elaeis guineensis* Jacq.)] separately using Principal Component Analysis and Agglomerative Clustering (Sujadi *et al.*, 2019; Yaakub *et al.*, 2023) [27, 30].

Materials and Methods

The experimental materials comprised 40 oil palms drawn from three different accessions: 240D × 281D and 80D × 281D (representing 17 *E. guineensis* palms) and oleifera-I (representing *E. oleifera* palms). These palms were selected from the oil palm gardens at the Indian Institute of Oil Palm Research (IIOPR), Pedavegi, Andhra Pradesh, and Palode, Kerala. All accessions were indigenously developed and maintained at Palode, Kerala.

Each palm was evaluated for 14 morphological parameters: 1. palm height (cm), 2. annual plant height increment (cm/ year), 3. girth at 25 cm above ground level (AGL) (cm), 4. girth at 50 cm AGL (cm), 5. sex ratio (number of female inflorescences: total inflorescences), 6. number of developing fruit bunches (DFBs), 7. number of leaves, 8. number of spindles, 9. petiole depth (cm), 10. petiole width (cm), 11. number of leaflets, 12. rachis length (cm), 13. leaflet length (cm), and 14. leaflet width (cm). Observations were recorded following the standard descriptors for oil palm as outlined by the International Plant Genetic Resources Institute (IPGRI, 2000) [14].

The collected data were subjected to statistical analysis to assess the extent of morphological diversity among palms. Principal Component Analysis (PCA) was employed to identify the most informative traits contributing to total variation, while Agglomerative Hierarchical Clustering (AHC) was applied to group palms into distinct clusters based on morphological similarity. Both analyses were performed using XLSTAT (Addinsoft, 2022) [2], an advanced statistical software integrated with Microsoft Excel. PCA was conducted following the methodology described by Jolliffe (2002) [15], where eigenvalues and eigenvectors of the correlation matrix are used to extract the main components. Cluster analysis was performed using Euclidean distance and Ward's minimum variance method, following standard protocols in multivariate analysis (Kaufman & Rousseeuw, 2005) [17]. PCA and clustering are well-established tools for diversity studies in crops (Jolliffe & Cadima, 2016) [16] and have been effectively applied to oil palm germplasm (Sujadi *et al.*, 2019; Yaakub *et al.*, 2023) [27, 30].

Results and Discussion

Morphological Variability

The evaluated oil palm genotypes showed considerable variation in growth, reproductive, and leaf traits as is presented in Table 1. Palm height ranged from 134 to 471 cm (mean = 293.3 cm), with annual increments of 16.75-37.38 cm/year (mean = 24.29 cm/year), indicating differences in growth vigour. Stem girth averaged 304.97 cm (25 cm AGL) and 296.93 cm (50 cm AGL), reflecting robust vegetative development. Similar variation in height and girth has been reported in oil palm germplasm studies, highlighting their importance as indicators of growth and yield potential (Martin *et al.*, 2022) [19]

Reproductive traits were also highly variable: the sex ratio spanned 0-1 (mean = 0.21), and developing fruit bunches ranged 0-12 (mean = 3.38). Such variation is critical, as lower sex ratios generally favour higher proportions of female inflorescences, which directly enhances bunch production (Corley & Tinker, 2016) [10]. Leaf architecture also differed considerably, with palms averaging 34 leaves, 305.6 leaflets, and a mean rachis length of 527.9 cm. Leaflet size averaged 105.1 × 6.3 cm, while petiole depth and width averaged 5.2 cm and 8.6 cm, respectively. Variability in leaf number, rachis length, and petiole size has been linked to differences in canopy efficiency and light interception, which are key determinants of yield (Samsudin *et al.*, 2025) [26].

Table 1: Summary statistics for 40 oil palms [23 *oleifera* (*Elaeis oleifera* HBK. cortes) and 17 *guineensis* (*Elaeis guineensis* Jacq.)]

Morphological Parameter	Minimum	Maximum	Mean	SD
Palm height (cm)	134	471	293.3	88.08277
Plant height/ year (cm)/year	16.75	37.375	24.29010417	4.813943
Girth at 25 cm AGL (cm)	243	372.5	304.97	41.12496
Girth at 50 cm AGL (cm)	220	364	296.93	41.76707
Sex Ratio	0	1	0.2109	0.321221
No. of DFBs	0	12	3.375	3.439495
No. of leaves	7	45	34.175	6.97206
No. of spindles	1	4	2.65	0.579567
Petiole depth (cm)	3.2	7.9	5.1675	1.164956
Petiole width (cm)	5	13.2	8.63	1.948333
No. of leaflets	236	356	305.6	25.07507
Rachis length (cm)	304	740	527.8875	129.2011
Leaflet length (cm)	53.9	155.2	105.135	29.25528
Leaflet width (cm)	3.3	8.6	6.2825	1.778632

Correlation Structure of Morphological Traits

The correlation analysis revealed clear patterns of association among oil palm morphological traits as presented in Table-2. Palm height was positively correlated with girth at 25 cm (r = 0.785, $p < 0.05$), girth at 50 cm (r = 0.690, $p < 0.05$), petiole width (r = 0.794, $p < 0.05$), rachis length (r = 0.707, $p < 0.05$), leaflet length (r = 0.801, $p < 0.05$), and leaflet width (r = 0.779, $p < 0.05$). These strong relationships reflect co-ordinated growth of structural organs, suggesting that palms that are taller also invest more in trunk robustness and canopy size. Similar structural integration of traits has been reported in oil palm and other perennials, where girth and leaf traits serve as indicators of vigour and biomass accumulation (Hardon *et al.*, 1985; Corley & Tinker, 2016; Popet *et al.*, 2022) [12, 10, 23].

The two girth measures were themselves highly correlated (r = 0.949), confirming measurement reliability. Both were also strongly linked to rachis length and leaflet width, underlining their importance as integrative indicators of vegetative robustness. Petiole width and depth were similarly associated with rachis and leaflet traits, supporting previous findings that petiole architecture underpins canopy expansion (Balakrishna *et al.*, 2017; Barcelos *et al.*, 2015) [4, 5].

Leaflet traits were highly correlated with rachis length (r = 0.600-0.886), confirming their role as drivers of canopy photosynthetic capacity. Studies of germplasm collections have likewise emphasized leaflet number and size as central to canopy development and yield efficiency (Camacho-Villalobos *et al.*, 2021) [8].

Reproductive traits showed contrasting associations. Sex ratio was negatively correlated with palm height, girth, rachis length, and leaflet traits, while number of developing fruit bunches (DFBs) correlated negatively with height (r = -0.577), rachis length (r = -0.533), and leaflet size (r = -0.611 to -0.515). These patterns suggest a resource allocation trade-off, whereby greater vegetative vigour may occur at the expense of reproductive efficiency. Such trade-offs have been observed in perennial crops including oil palm (Breure & Corley, 1983; Weiner, 2004; Osorio-Guarín *et al.*, 2019) [7, 29, 22].

Leaf number correlated positively with spindle number (r = 0.536) and DFBs (r = 0.432) but negatively with rachis length (r = -0.373), suggesting independence between leaf quantity and size. This distinction has been highlighted in crop physiology, where canopy productivity is shaped by both production rate and individual leaf dimensions (Legros *et al.*, 2009) [18]. Plant height increment per year correlated modestly with sex ratio (r = 0.346), suggesting that faster-growing palms may invest proportionally more in reproductive effort, echoing developmental studies of palm flowering (Adam *et al.*, 2011) [1].

Table 2: Correlation matrix (Pearson (n)) for 40 oil palms [23 oleifera (*Elaeis oleifera* HBK. cortes) and 17 guineensis (*Elaeis guineensis* Jacq.)]

Variables	Palm height (cm)	Plant height/ year (cm)/year	Girth at 25 cm AGL (cm)	Girth at 50 cm AGL (cm)	Sex Ratio	No. of DFBs	No. of leaves	No. of spindles	Petiole depth (cm)	Petiole width (cm)	No. of leaflets	Rachis length (cm)	Leaflet length (cm)	Leaflet width (cm)
Palm height (cm)	1	0.142	0.785	0.690	-0.358	-0.577	-0.129	-0.230	0.565	0.794	0.226	0.707	0.801	0.779
Plant height/ year (cm)/year	0.142	1	0.037	-0.039	0.346	0.318	0.295	0.069	-0.123	-0.034	-0.150	-0.324	-0.254	-0.258
Girth at 25 cm AGL (cm)	0.785	0.037	1	0.949	-0.394	-0.324	-0.018	-0.200	0.581	0.727	0.304	0.675	0.665	0.743
Girth at 50 cm AGL (cm)	0.690	-0.039	0.949	1	-0.388	-0.305	-0.043	-0.164	0.633	0.744	0.355	0.687	0.626	0.760
Sex Ratio	-0.358	0.346	-0.394	-0.388	1	0.228	-0.259	-0.112	-0.248	-0.313	-0.162	-0.373	-0.427	-0.440
No. of DFBs	-0.577	0.318	-0.324	-0.305	0.228	1	0.432	0.351	-0.397	-0.432	-0.114	-0.533	-0.611	-0.515
No. of leaves	-0.129	0.295	-0.018	-0.043	-0.259	0.432	1	0.536	-0.292	-0.187	-0.301	-0.373	-0.165	-0.335
No. of spindles	-0.230	0.069	-0.200	-0.164	-0.112	0.351	0.536	1	-0.230	-0.109	-0.130	-0.292	-0.185	-0.257
Petiole depth (cm)	0.565	-0.123	0.581	0.633	-0.248	-0.397	-0.292	-0.230	1	0.705	0.271	0.739	0.662	0.674
Petiole width (cm)	0.794	-0.034	0.727	0.744	-0.313	-0.432	-0.187	-0.109	0.705	1	0.471	0.825	0.796	0.844
No. of leaflets	0.226	-0.150	0.304	0.355	-0.162	-0.114	-0.301	-0.130	0.271	0.471	1	0.600	0.301	0.454
Rachis length (cm)	0.707	-0.324	0.675	0.687	-0.373	-0.533	-0.373	-0.292	0.739	0.825	0.600	1	0.866	0.886
Leaflet length (cm)	0.801	-0.254	0.665	0.626	-0.427	-0.611	-0.165	-0.185	0.662	0.796	0.301	0.866	1	0.825
Leaflet width (cm)	0.779	-0.258	0.743	0.760	-0.440	-0.515	-0.335	-0.257	0.674	0.844	0.454	0.886	0.825	1

Values in bold are different from 0 with a significance level alpha=0.05

Principal Component Analysis of Trait Variability

The PCA was statistically supported (Bartlett's $\chi^2 = 516.85$, df = 91, $p < 0.0001$; KMO = 0.774), confirming suitability of the dataset for multivariate analysis (Camacho-Villalobos *et al.*, 2021) [8]. Four components with eigenvalues > 1 were retained, explaining 81.36% of the variance. Table-3 enumerates eigenvalues, variability% and cumulative variability explained by all 14 factors computed. Figure-1 represents the same graphically in the form of scree plot.

PC1, accounting for 50.64% of the variance, was dominated by structural traits: palm height, girth, rachis length, petiole width, and leaflet size. These traits clustered as a "structural vigour" dimension, reflecting canopy and trunk robustness. Similar patterns were reported in oil palm and coconut, where leaf and stem architecture consistently dominate the first PCA axis (Perera *et al.*, 2010; Popet *et al.*, 2022) [, 23].

PC2 explained 13.53% of the variance and was defined by number of leaves and spindles. This "leaf production" axis separated palms with high canopy turnover from those with fewer leaves, reinforcing the importance of leaf production rate as a predictor of yield potential (Corley & Tinker, 2016; Legros *et al.*, 2009) [10, 18].

PC3 (9.74%) captured a growth-reproduction trade-off, with positive loadings for plant height increment and sex ratio. This axis reflects alternative allocation strategies among genotypes: those investing in rapid vegetative elongation exhibited distinct reproductive patterns, consistent with allocation theory in perennial crops (Weiner, 2004; Osorio-Guarín *et al.*, 2019) [29, 22].

PC4 (7.45%) highlighted variation in leaflet number and DFBs, suggesting that high leaflet proliferation may be linked with reduced reproductive efficiency. Comparable findings were observed in hybrid characterization studies, where foliage traits contributed to variation in bunch production (Research Square, 2025) [24].

Table 3: Eigenvalues, Variability% accounted for and Cumulative variability accounted for by 14 computed Principal Components.

	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12	PC13	PC14
Eigenvalue	7.09	1.89	1.36	1.04	0.69	0.58	0.40	0.31	0.27	0.14	0.09	0.07	0.04	0.02
Variability (%)	50.64	13.53	9.75	7.45	4.91	4.13	2.89	2.22	1.95	0.99	0.63	0.47	0.29	0.17
Cumulative (%)	50.64	64.17	73.91	81.36	86.27	90.40	93.28	95.50	97.46	98.44	99.07	99.54	99.83	100.00

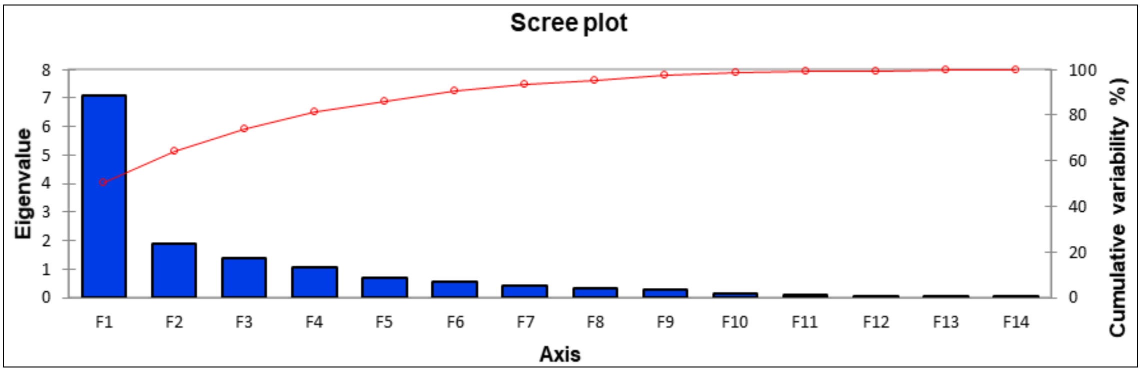

Fig 1: Scree Plot for 14 computed Principal Components.

Biplot Interpretation and Genotypic Differentiation

The PCA biplot grouped traits into biologically coherent clusters: structural vigour (height, girth, rachis, leaflets) dominated PC1, leaf production (leaf and spindle number) defined PC2, while reproductive traits (sex ratio, DFBs) opposed vegetative vigour. This graphical separation mirrors the antagonistic correlations observed earlier, reinforcing the dual axis of palm growth - vegetative robustness versus reproductive efficiency. The PCA biplot is presented as Figure-2.

Genotypes were clearly differentiated along these axes. Eg115, Eg209, and Eo14 scored highly on both PC1 and PC2, indicating strong vegetative vigour combined with prolific canopy turnover. Such genotypes are promising candidates for breeding programs seeking palms that balance robustness with productivity. Conversely, Eg37 and Eg99 scored negatively on PC1, reflecting weaker vegetative development, while Eg117 and Eg205 differentiated along PC3 and PC4, suggesting alternative growth-reproduction strategies. Similar genotypic stratification was reported in germplasm collections, highlighting the value of PCA for guiding selection (Barcelos *et al.*, 2015; Camacho-Villalobos *et al.*, 2021) [5, 8].

Overall, the integration of correlation and PCA analyses demonstrates that structural vigour traits dominate morphological variability, while reproductive parameters define important trade-offs. These findings align with multivariate studies in oil palm (Balakrishna *et al.*, 2017; Popet *et al.*, 2022) [4, 23] and support the use of PCA to identify elite genotypes combining canopy development with reproductive balance. By streamlining complex datasets into biologically meaningful dimensions, PCA reinforces its utility as a breeding tool, enabling the selection of palms with desirable trait combinations for yield improvement (Corley & Tinker, 2016; Research Square, 2025) [10, 24].

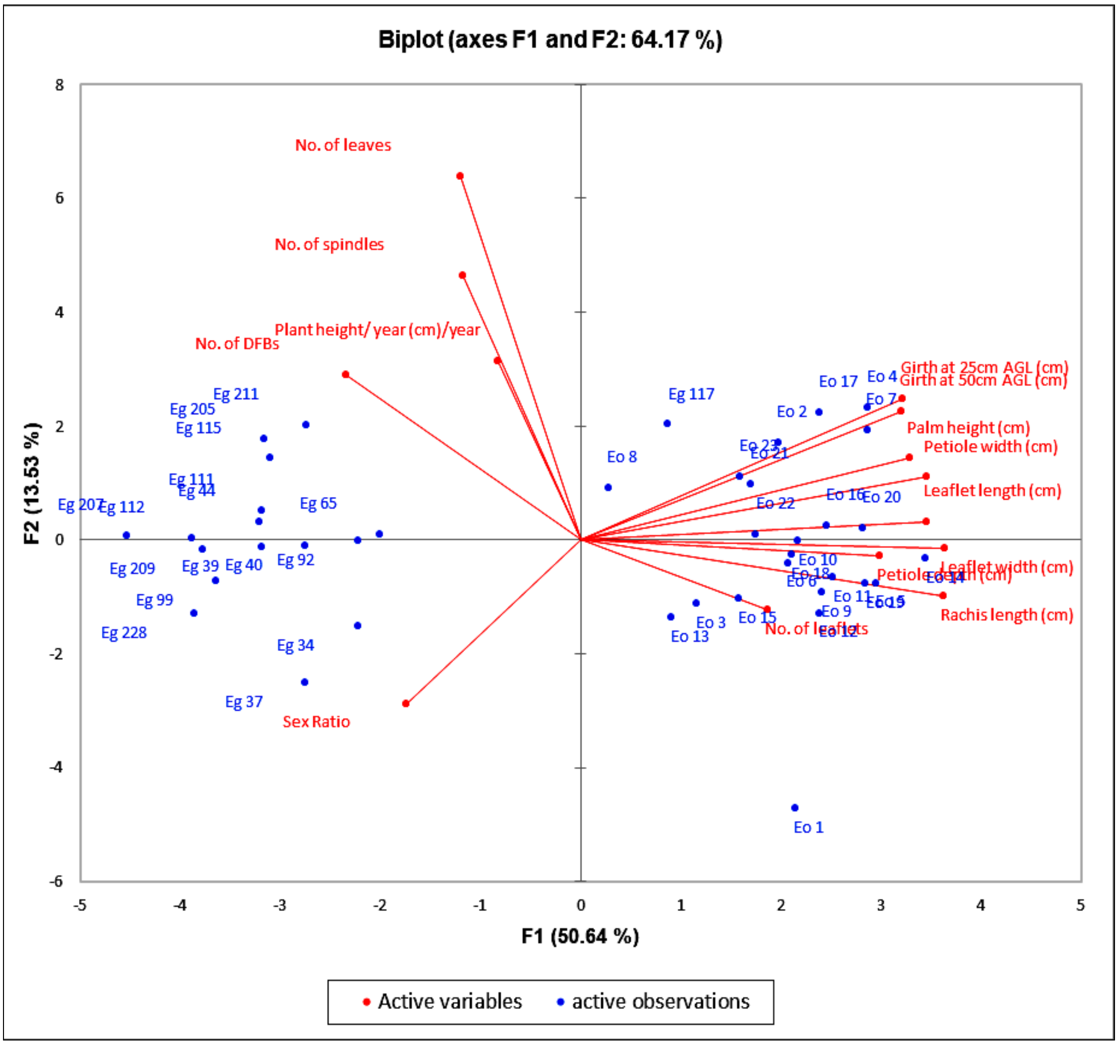

Fig 2: PCA Biplot

Agglomerative Hierarchical Clustering

AHC grouped the genotypes into three major clusters, with between-class variance (77.64%) substantially exceeding within-class variance (22.36%), confirming reliable partitioning of morphological diversity. Table-4 presents Cluster centroids for 14 morphological parameters of 40 oil palms and Table-5 provides distances between Cluster centroids.

Table 4: Cluster centroids for 14 Morphological Parameters of of 40 oil palms [23 oleifera (*Elaeis oleifera* HBK. cortes) and 17 guineensis (*Elaeis guineensis* Jacq.)]

Cluster	Palm Height (cm)	Plant height/year (cm)/year	Girth at 25 cm AGL (cm)	Girth at 50 cm AGL (cm)	Sex Ratio	No. of DFBs	No. of leaves	No. of spindles	Petiole Depth (cm)	Petiole Width (cm)	No. of leaflets	Rachis Length (cm)	Leaflet Length (cm)	Leaflet Width (cm)
Cluster-1	316.75	20.71	321.21	319.68	0.10	2.08	30.17	2.42	6.13	9.99	317.50	665.50	131.37	7.83
Cluster-2	382.58	25.47	341.77	328.00	0.06	1.33	34.92	2.67	5.53	9.87	313.83	576.33	119.97	7.40
Cluster-3	208.75	26.09	265.19	256.56	0.41	5.88	36.63	2.81	4.18	6.68	290.50	388.34	74.34	4.29

Table 5: Distances between the Cluster centroids

	Cluster-1	Cluster-2	Cluster-3
Cluster-1	0.00	113.87	315.75
Cluster-2	113.87	0.00	281.42
Cluster-3	315.75	281.42	0.00

Cluster 1 (12 genotypes, central object Eo21): Palms of intermediate height (316.8 cm) and moderate girth (321.2 cm), but with long rachises (665.5 cm) and large leaflets (131.4 × 7.8 cm). These genotypes combined strong canopy development with low reproductive allocation (sex ratio 0.10, DFBs 2.08).

Cluster 2 (12 genotypes, central object Eo6): Tallest palms (382.6 cm), largest girths (341.8 cm), and highest leaf production (34.9 leaves), paired with moderate rachis length (576.3 cm). Reproductive effort was lowest (sex ratio 0.06, DFBs 1.33), reflecting a structural growth orientation.

Cluster 3 (16 genotypes, central object Eg99): Shortest palms (208.8 cm), smallest girths (265.2 cm), and lowest rachis lengths (388.3 cm), but highest reproductive effort (sex ratio 0.41, DFBs 5.88).

The greatest divergence occurred between Clusters 1 and 3 (distance 315.8), with Cluster 2 intermediate but closer to Cluster 1. Table-6 enumerates cluster wise distribution of genotypes and Figure-3 depicts the dendrogram representing the clustering pattern of respective genotypes.

Table 6: Cluster-wise distribution of 40 oil palms and related statistics

	Cluster-1	Cluster-2	Cluster-3
Genotypes	Eo 1	Eo 2	Eg 34
	Eo 5	Eo 3	Eg 37
	Eo 9	Eo 4	Eg 39
	Eo 11	Eo 6	Eg 40
	Eo 12	Eo 7	Eg 44
	Eo 15	Eo 8	Eg 65
	Eo 16	Eo 10	Eg 92
	Eo 19	Eo 13	Eg 99
	Eo 20	Eo 14	Eg 111
	Eo 21	Eo 17	Eg 112
	Eo 22	Eo 18	Eg 115
	Eo 23	Eg 117	Eg 205
	-	-	Eg 207
	-	-	Eg 209
	-	-	Eg 211
	-	-	Eg 228
No. of Genotypes	12.00	12.00	16.00
Sum of weights	12.00	12.00	16.00
Within-Cluster variance	5237.23	11648.41	3866.72
Minimum distance to centroid	25.24	34.88	27.25
Average distance to centroid	61.47	97.97	55.68
Maximum distance to centroid	143.05	147.71	122.48

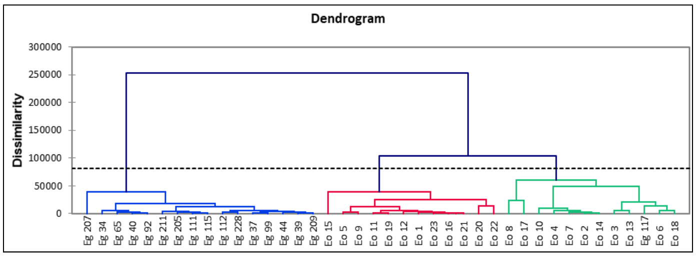

Fig 3: Dendrogram representing Agglomerative hierarchical clustering (AHC) of 40 oil palms [23 *oleifera* (*Elaeis oleifera* HBK. cortes) and 17 *guineensis* (*Elaeis guineensis* Jacq.)]

The clustering reflected clear species differences. Clusters 1 and 2 contained mostly *E. oleifera*, characterized by stronger vegetative structures, broader canopies, and lower reproductive ratios. These patterns are consistent with *oleifera*'s slow-growing, long-lived morphology and its value as a genetic reservoir for structural vigour (Camacho-Villalobos *et al.*, 2021; Corley & Tinker, 2016) [8, 10]. Cluster 3, dominated by *E. guineensis*, exhibited shorter palms with smaller canopies but higher reproductive allocation, in line with domestication-driven emphasis on yield (Adam *et al.*, 2011; Osorio-Guarín *et al.*, 2019) [1, 22].

Variation within *oleifera* was evident: Cluster 1 emphasized rachis length and leaflet expansion, while Cluster 2 emphasized overall height, girth, and leaf production. Such intra-specific divergence, also noted in South American germplasm (Camacho-Villalobos *et al.*, 2021) [8], highlights opportunities for breeders to tailor canopy and reproductive traits through selective introgression.

Cluster 3's reproductive orientation illustrates the well-documented trade-off between vegetative robustness and reproductive output (Weiner, 2004) [29]. Interestingly, Eg117 grouped with *oleifera*-like Cluster 2 despite being *guineensis*, suggesting morphological convergence or introgression - a pattern also observed in interspecific hybrid characterization studies (Research Square, 2025) [24].

The integration of descriptive statistics and clustering demonstrates that morphological diversity in oil palm is structured both by species-level differentiation and within-species variability. *E. oleifera* contributes canopy robustness and longevity, while *E. guineensis* emphasizes reproductive allocation. Identifying genotypes like those in Cluster 2 (which combine height, girth, and leaf production with reduced reproductive burden) may be especially valuable for developing hybrids that balance structural vigour with yield efficiency (Hardon *et al.*, 1985; Barcelos *et al.*, 2015) [12, 5].

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