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Multi-Trait Evaluation of Cashew Clones for Reproductive Efficiency, Nut Quality, and Morphological Diversity

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Abstract

Cashew (*Anacardium occidentale* L.) production in Nigeria is hindered by the limited use of improved varieties, whose nut quality and reproductive performance have been well documented. This study evaluated twelve cashew clones from the Cocoa Research Institute of Nigeria (CRIN) germplasm collection for nut quality, pollen viability, and morphological traits. Analysis of variance, Pearson correlation, principal component analysis, and a multi-trait performance index were used. Significant genetic variation was found across all traits. Nut weight ranged from 4.27 g (EU202) to 11.34 g (OCJ9), while kernel weight ranged from 1.50 g (EU202) to 3.75 g (OCJ9). Positive correlations ($r > 0.96$) between nut weight, kernel weight, and nut length confirmed that selecting for any of these traits will improve the others simultaneously. Shelling percentage was negatively correlated with nut size ($r = -0.719$), showing a size-efficiency trade-off. Pollen tube length and germination percentage varied independently from nut size and kernel recovery traits (nut weight, kernel weight, and nut length). This independence means that reproductive efficiency and nut size traits can each be improved without compromising the other. Principal component analysis separated a nut size efficiency axis from a reproductive-morphological axis, showing multi-dimensional diversity. The multi-trait performance index ranked OCJ9 first (index = 3.45), combining the largest nut size (11.34 g), the highest kernel weight (3.75 g), and good pollen performance. ORO3 ranked second (index = 1.44) for its outstanding pollen germination (98.00%) and pollen tube length (133.33 μm), and YS103 ranked third (index = 0.75) with

the highest germination rate (98.50%). BEL22 ranked fourth overall. These clones are recommended as priority parents for cashew improvement in Nigeria.

Keywords: Cashew, *Anacardium occidentale*, Nut Quality, Pollen Viability, Germination, Multi-trait Index.

Introduction

Cashew (*Anacardium occidentale* L.) is a tropical evergreen tree belonging to the Anacardiaceae family. It is grown mainly for its edible kernel and the juicy pseudo-fruit known as the cashew apple (Bolade and Adeyinka, 2024). Native to northeastern Brazil, cashew was introduced to West Africa in the 16th century by Portuguese traders and expanded as a commercial crop from the mid-20th century (Oliveira et al., 2019). Today, West Africa leads the world in raw cashew nut (RCN) production, supplying 49-60% of global output in recent years, with Côte d'Ivoire producing over 1 million metric tonnes annually, followed by Nigeria, Benin, Guinea-Bissau, and Ghana (Ecofin Agency, 2026).

Despite its economic importance, cashew productivity in Nigeria and much of West Africa remains low and variable, typically 350-500 kg/ha under smallholder conditions, compared with 1,000-1,500 kg/ha in leading Asian producers such as India and Vietnam (Kadjo et al., 2025). Key challenges include widespread use of unimproved landraces and open-pollinated seedlings, aging plantations, poor post-harvest handling, pests and diseases, and low fruit set (Adeniyi and Nduka 2022; Bello et al., 2019; Adeigbe et al., 2016; Aliyu et al., 2014). Nut quality traits such as kernel weight, shelling percentage, and kernel out turn directly

determine commercial value and export performance. Reproductive traits such as pollen viability, germination percentage, and pollen tube growth play a key role in fertilization success and yield stability (Sriyal et al., 2025; Babatunde et al., 2025a). Vegetative traits, including tree habit, branching pattern, and leaf size, affect canopy structure, light interception, resource use, and long-term orchard output (Kadjo et al., 2025).

Breeding work in Nigeria, led mainly by CRIN, has focused on germplasm collection, multi-environment testing, and selection for better kernel recovery (Adeniyi et al., 2025; Babatunde et al., 2023). Reproductive traits show considerable genetic variation and can often be improved separately from nut quality, giving breeders the opportunity to raise fruit set and yield stability without sacrificing kernel recovery (Sriyal et al., 2025).

This study evaluates twelve cashew clones in the CRIN collection for key nut quality traits (nut weight, kernel weight, shelling percentage), pollen viability and tube growth, and selected vegetative traits.

Materials and Methods

Experimental Site and Plant Material

The study was carried out at the Cocoa Research Institute of Nigeria (CRIN), Ibadan,

Nigeria (7°23' N, 3°50' E; 200 m above sea level). The location lies within the humid forest zone and has a bimodal rainfall pattern with an annual mean of 1,200-1,500 mm and an average temperature of about 27 °C. Twelve cashew (*Anacardium occidentale* L.) clones maintained in the CRIN germplasm collection (KD102, YS103, EU202, BEL36, YS203, OCJ9, OCJ2, EN103, CR102, ORO9, BEL22, and ORO3) were evaluated.

Nut Quality Evaluation

Based on Adewale et al. (2010) mature cashew nuts were harvested at physiological maturity, approximately 12-14 weeks after anthesis, during the main fruiting period between February and April 2024. For each clone, ten nuts were randomly collected. The nuts were separated from the apples, cleaned to remove adhering tissues, and air-dried under ambient laboratory conditions (28-32 °C and 60-70% relative humidity) for seven days to stabilize moisture content prior to assessment.

Nut weight was determined using an analytical balance, while nut length, width, and girth were measured with a digital Vernier caliper. Nuts were cracked manually, and kernel and shell weights were recorded separately. Shelling percentage, kernel-to-shell ratio, nut shape index, and size index were calculated using standard formulas to describe nut quality and size attributes.

Pollen Collection

Pollen grains were collected from healthy, fully opened hermaphrodite flowers during the morning period between 08:00 and 09:00 h, when pollen viability is optimal in cashew. Flowers were randomly selected from each clone to ensure representative sampling. Anthers were carefully excised from six flowers per clone using sterile forceps and gently tapped to release pollen grains into sterile collection tubes containing a 1:3 (v/v) solution of glacial acetic acid and 70% ethanol, which served as a temporary preservative to maintain pollen integrity prior to analysis. Preserved pollen samples were subsequently used for in vitro germination and viability assessments.

In Vitro Pollen Germination

Pollen germination was assessed on two culture media modified from standard protocols. The first medium contained sucrose, boric acid, and agar, while the second medium consisted of sucrose supplemented with calcium nitrate, boric acid, and agar. Sterilized media were poured into Petri dishes, and pollen grains were evenly distributed on the solidified surface. Three replicate plates per clone were prepared for each medium and maintained under natural laboratory conditions (approximately 25 °C and 60-70% relative humidity) in darkness. A pollen grain was considered germinated when the pollen tube exceeded the grain diameter. Environmental conditions during the 24-hour pollen tube elongation phase were maintained consistently at a room temperature of approximately 25°C and a relative humidity of 60-70%. These conditions were monitored throughout the incubation period to minimize environmental

variability that could affect pollen kinetics, as temperature fluctuations are known to significantly alter cashew pollen tube elongation rates.

Morphological Characterization

Morphological evaluation followed the cashew descriptors outlined by the International Board for Plant Genetic Resources (IBPGR, 1986). Observations were made during the vegetative phase from August to October 2024, when traits remain stable.

Qualitative traits assessed included tree growth habit, branching pattern, leaf shape, young leaf color, and leaf apex form. Quantitative measurements targeted leaf size, with ten fully expanded, healthy leaves sampled per clone from the third to fifth nodes of current season lateral shoots at 1.5-2.0 m height. Leaf length was measured from petiole insertion to apex along the midrib using a graduated ruler.

Statistical Analysis

All statistical analyses were performed using R software (version 4.5.2). Pollen tube length was measured from digital micrographs using ImageJ software (version 1.54p, 2025). Descriptive statistics were computed for all quantitative traits, and qualitative traits were summarized using frequency distributions. One-way analysis of variance (ANOVA) was conducted to test for significant differences among cashew clones. Mean separation was done using Duncan's Multiple Range Test (DMRT) at $P \leq 0.05$ via the agricolae package in R, as indicated in the mean table. Pearson correlation analysis and principal component analysis were applied to examine relationships among quantitative traits and to identify major sources of variation. A multi-trait selection index was calculated using standardized values of nut quality, pollen, and vegetative traits, and clones were ranked based on index values, with higher scores indicating better overall performance. The Multi-Trait Performance Index (MTPI) was computed as: $MTPI = \sum (w_i \times z_i)$, where z_i is the standardized value (z-score) of the i -th trait for each clone, and w_i is the selection weight assigned to that trait based on its relative economic importance. Traits with greater breeding value (nut weight, kernel weight, and pollen germination) were assigned higher weights, while shelling percentage, pollen tube length, and leaf size received proportionally lower weights. This approach follows the weighted selection index framework described by Smith (1936).

Results

The evaluation showed clear genetic variation in nut quality traits among the twelve cashew clones (Table 1). Nut weight ranged from 4.27 g in EU202 to 11.34 g in OCJ9, representing about a 2.7-fold difference that is of direct economic importance. The clones YS203 (11.22 g), OCJ9 (11.34 g), and ORO9 (11.15 g) produced the heaviest nuts, all exceeding 11 g. OCJ2 and BEL22 also recorded nut weights above 8 g, placing them in an intermediate high-yielding group. Analysis of variance confirmed highly significant differences among clones for all nut quality parameters, indicating that real genetic differences exist and are suitable for selection.

Kernel weight ranged from 1.50 g in EU202 to 3.75 g in OCJ9 (Table 1). OCJ9 produced the heaviest kernels, followed by YS203 (3.44 g) and ORO9 (2.83 g). The positive correlation ($r = 0.968$) between nut weight and kernel weight (Table 4) confirms that selecting for larger nuts will also improve kernel yield.

Shell weight varied from 2.73 g in EU202 to 7.97 g in ORO9. Clones with larger nuts generally also had heavier shells. Among the accessions, KD102 (3.11 g), EU202 (2.73 g), and YS103 (3.65 g) had the lightest shells, while ORO9 (7.97 g), YS203 (7.70 g), and OCJ9 (7.15 g) had the heaviest. This pattern reflects the well-known biological trade-off between absolute nut size and proportional kernel recovery.

These differences across the twelve clones are further illustrated in Figure 1, which shows the distribution of nut weight (A), kernel weight (B), shelling percentage (C), and kernel-shell ratio (D). The boxplots confirm the wide spread in nut weight and kernel weight, with OCJ9, YS203, and ORO9 clearly separated at the upper end, while EU202 and KD102 remained at the lower end. Shelling percentage was higher in clones with smaller nuts, although the clones produced lighter nuts, a greater proportion of the nut was kernel. This agrees with the negative correlation recorded between size and shelling percentage.

Table 1. Mean performance of twelve accessions for six characters

Accessions	Nut wt	Nut Lgt	Nut width	Nut Girth	Kernel wt	Shell wt
KD102	4.78 ^{bc}	2.68 ^{bc}	1.91 ^c	1.45 ^{bcd}	1.65 ^c	3.11 ^c
YS103	5.50 ^{bc}	2.94 ^{bc}	2.12 ^{cde}	1.29 ^{cd}	1.77 ^c	3.65 ^{cde}
EU202	4.27 ^c	2.55 ^c	1.97 ^{de}	1.13 ^d	1.50 ^c	2.73 ^c
BEL36	7.04 ^{bc}	3.08 ^b	2.28 ^{cde}	1.50 ^{bcd}	1.99 ^c	4.95 ^{cde}
YS203	11.22 ^a	3.99 ^a	2.52 ^{bc}	1.72 ^{bc}	3.44 ^{ab}	7.70 ^{ab}
OCJ9	11.34 ^a	3.79 ^a	2.99 ^a	1.84 ^{ab}	3.75 ^a	7.15 ^{ab}
OCJ2	8.43 ^{ab}	3.19 ^b	2.43 ^{bcd}	1.57 ^{bcd}	2.41 ^{bc}	5.96 ^{abc}
EN103	5.67 ^{bc}	2.87 ^{bc}	1.95	1.42 ^{bcd}	2.18 ^{bc}	3.42 ^{de}
CR102	6.86 ^{bc}	3.05 ^b	2.17 ^{cde}	1.49 ^{bcd}	2.23 ^{bc}	4.58 ^{cde}
ORO9	11.15 ^a	3.69 ^a	2.79 ^{ab}	2.24 ^a	2.83 ^{abc}	7.97 ^a
BEL22	8.17 ^{ab}	3.17 ^b	2.36 ^{bcd}	1.55 ^{bcd}	2.52 ^{abc}	5.56 ^{bcd}
ORO3	7.17 ^{bc}	3.12 ^b	2.19 ^{cde}	1.47 ^{bcd}	2.18 ^{bc}	4.81 ^{cde}
F. sign	**	***	**	*	*	**

Means followed by the same letter(s) are not significantly different according to DMRT ($P < 0.05$)

, **, * - Significant at $P \leq 0.05$, 0.01, and 0.001*

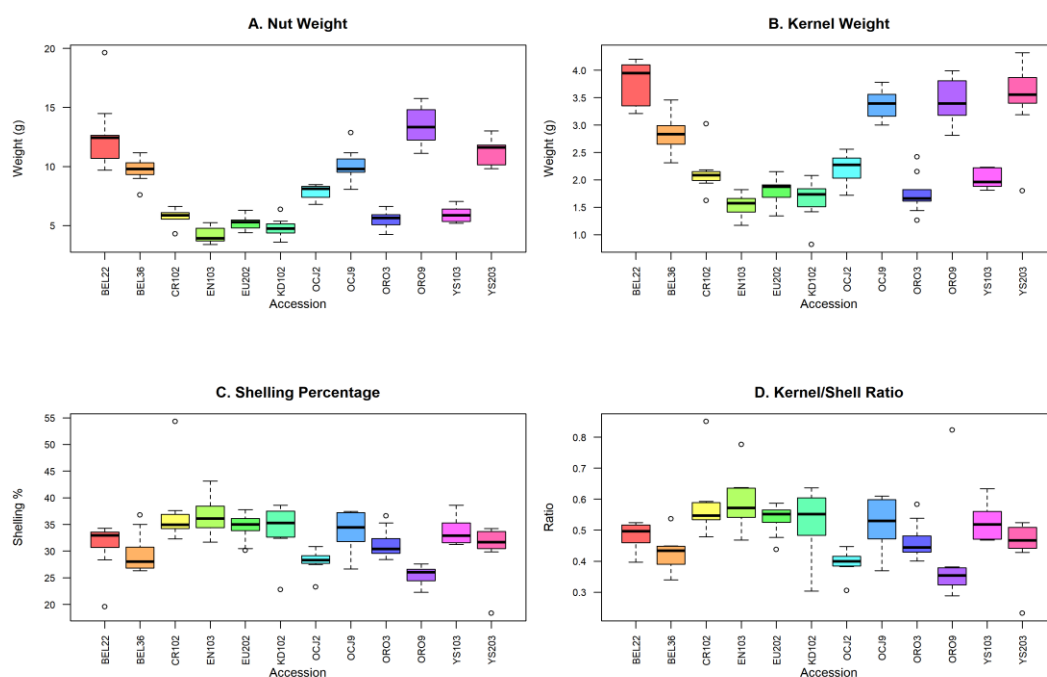


Figure 1. Variation in Economic Nut Quality Traits Across Cashew Accessions: (A) Nut Weight, (B) Kernel Weight, (C) Shelling Percentage, (D) Kernel-Shell Ratio

Pollen viability assessment revealed significant genetic variation in reproductive capacity (Table 2). Pollen tube length varied from 50.15 μm in ORO9 to 177.89 μm in EU202 (Figure 2A), showing differences in pollen vigor and fertilization potential. EU202 showed the best pollen performance, followed by ORO3 at 133.33 μm and OCJ9 at 131.92 μm . Longer pollen tubes show a better ability to travel through the style to reach the ovule, which directly affects fruit set and yield stability.

Germination percentage ranged from 49.50% in BEL36 to 98.50% in YS103 (Figure 2B), with high rates also in ORO3 and YS203. Germination percentage showed only negligible correlation with nut quality traits ($r < 0.15$), which means that nut quality and pollen germination are controlled by largely separate genetic pathways. This is useful for breeding because it allows selection for better pollen germination without risking a loss in nut quality, provided the two traits are not negatively correlated.

Table 2: Analysis of Variance for Pollen Viability Traits

Trait	Df	MS	F-value	Significance
Pollen Tube Length	11	8,820.57	39.62	***
Germination Rate	11	1,647.47	3.43	**

***, ** indicate significance at $P < 0.001$ and $P < 0.01$, respectively.

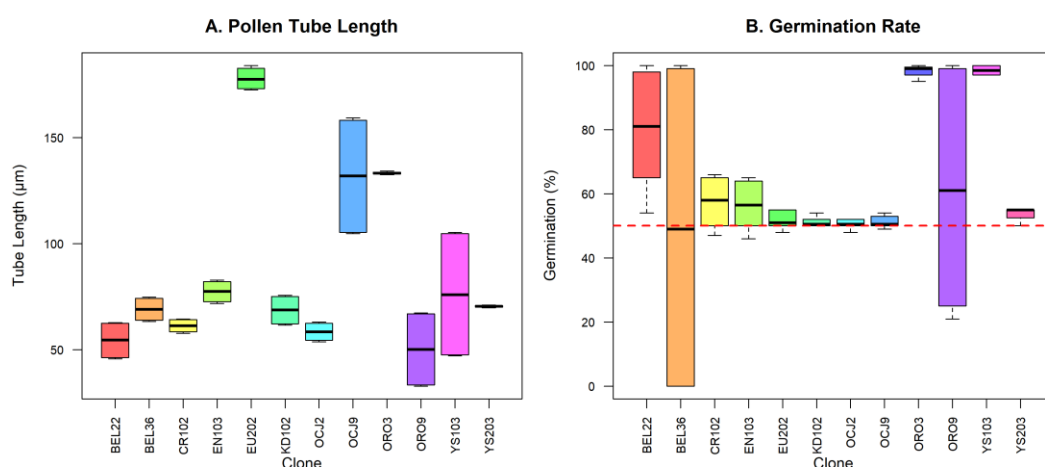


Figure 2: Reproductive Efficiency of Cashew Accessions: (A) Pollen Tube Length and (B) Germination Percentage Across Two Culture Media.

Morphological characterization showed clear differences in canopy architecture across the germplasm (Table 3). Tree habit ranged from upright and open in 58.3% of clones to spreading in 33.3%. Leaf morphology showed 66.7% with oblong shapes and 33.3% with obovate forms. Young leaf colour was evenly split between green and green-yellow types, each making up 50% of the collection. Leaf apex characteristics further separated the clones, with 58.3% having rounded tips and 41.7% showing indented apices.

Table 3: Frequency Distribution of Qualitative Morphological Traits

Trait	Category	Frequency	Percentage
Tree Habit	Upright and Open	7	58.3
	Spreading	4	33.3
	Intensive and Open	1	8.3
Leaf Shape	Oblong	8	66.7
	Obovate	4	33.3
Young Leaf Colour	Green	6	50.0
	Green Yellow	6	50.0
Leaf Apex	Rounded	7	58.3
	Indented	5	41.7

The correlation matrix showed a tightly linked group of nut quality traits (Table 4, Figure 3). Nut weight, kernel weight, and nut length had positive correlations exceeding 0.96, indicating that these traits are largely controlled by the same genetic factors. This means that selecting for any one of these traits will improve the others at the same time. Shelling percentage showed negative correlations with size-related traits ($r = -0.719$ with nut weight), confirming the biological trade-off between absolute nut size and the proportion of kernel in the nut.

Reproductive traits were largely independent of nut quality, with pollen tube length and germination percentage showing weak correlations with nut traits (Figure 3). The near-zero correlation ($r = 0.047$) between the two pollen traits suggests that germination capacity and tube elongation are controlled by different genetic pathways.

Table 4. Pearson Correlation Matrix Among Nut, Pollen, and Morphological Traits

Trait	Nut Weight	Kernel Weight	Shelling %	Nut Length	Pollen Tube Length	Germination	Leaf Size
Nut Weight	1.000	0.968	-0.719	0.969	-0.370	-0.094	-0.527
Kernel Weight	0.968	1.000	-0.542	0.964	-0.301	-0.109	-0.540
Shelling %	-0.719	-0.542	1.000	-0.652	0.333	-0.013	0.172
Nut Length	0.969	0.964	-0.652	1.000	-0.366	-0.131	-0.461
Pollen Tube Length	-0.370	-0.301	0.333	-0.366	1.000	0.047	0.187
Germination	-0.094	-0.109	-0.013	-0.131	0.047	1.000	-0.353
Leaf Size	-0.527	-0.540	0.172	-0.461	0.187	-0.353	1.000



Figure 3: Correlation Structure Between Reproductive Efficiency and Nut Quality Traits Principal component analysis showed clear patterns of genetic diversity (Table 5, Figure 4).

The first principal component captured the main size efficiency trade-off, with nut weight (25.09% contribution), nut length (23.90%), and kernel weight (23.05%) loading positively,

while shelling percentage (13.65%) loaded negatively. This component separates large nutted clones with lower shelling percentages from small nutted, higher efficiency types.

The second principal component was dominated by pollen germination percentage (63.65% contribution) and leaf size (32.70%). Its independence from PC1 confirms that reproductive efficiency and vegetative characteristics vary separately from nut quality. This multi-dimensional diversity means that the germplasm covers a wide range of possible trait combinations, giving breeders much material to work with when creating varieties for different production systems.

Table 5. PCA Loadings for Integrated Multi-Trait Analysis

Trait	PC1 Loading	PC2 Loading	PC1 Contribution	PC2 Contribution
Nut Weight	0.988	-0.052	25.091	0.207
Nut Length	0.965	-0.105	23.900	0.855
Kernel Weight	0.947	-0.030	23.048	0.068
Shelling Pct	-0.729	0.135	13.650	1.423
Leaf Size	-0.579	-0.647	8.608	32.701
Pollen TL	-0.469	0.119	5.651	1.096
Germination	-0.045	0.903	0.052	63.650

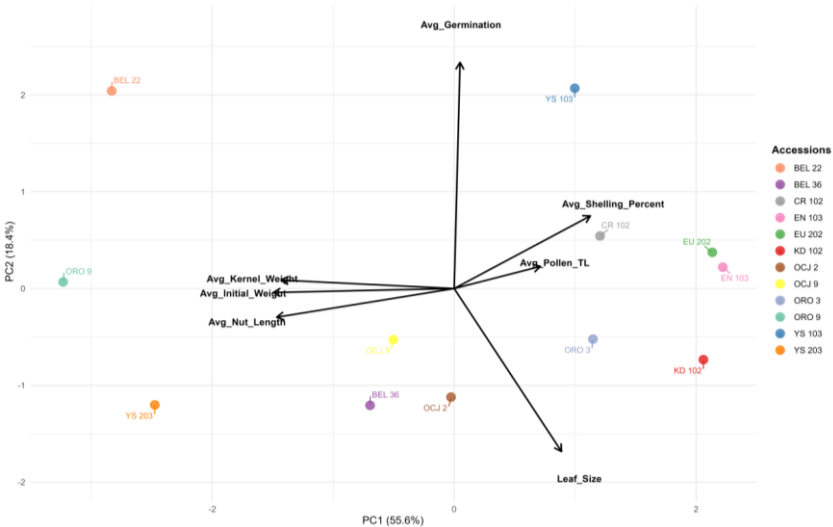


Figure 4: Principal Component Biplot for Integrated Multi-Trait Diversity Assessment

The multi-trait performance index brought together all measured traits into a single ranking (Table 6, Figure 5). OCU9 came out as the best-performing clone (index = 3.45), driven by its large nut weight (11.34 g), the highest kernel weight (3.75 g), acceptable germination (51.17%), and good pollen tube growth (131.92 μm). This clone represents a well-rounded combination across all selection criteria.

ORO3 ranked second (index = 1.44) with a different strength profile. Although it produced smaller nuts (7.17 g), ORO3 stood out in reproductive traits with very high germination (98.00%) and good pollen tube length (133.33 μ m). YS103 came third (index = 0.75), offering balanced performance with moderate nut weight (5.50 g), and the highest germination rate (98.50%).

Among the large-nutted clones, ORO9 (11.15 g), YS203 (11.22 g), and OCJ9 (11.34 g) were the top three for nut weight. However, their multi-trait ranking was influenced by performance in reproductive and shelling traits. Lower-ranked clones such as EU202 and KD102 had the smallest nuts but showed useful pollen performance, which gives them some value in crosses aimed at improving reproductive efficiency.

Table 6. Clone Ranking Based on Multi-Trait Performance Index

Rank	Clone	MTI	Nut Weight	Shelling %	Pollen Germination	Pollen TL
1	OCJ9	3.45	11.34	33.78	51.17	131.92
2	ORO3	1.44	5.50	31.39	98.00	133.33
3	YS103	0.75	5.50	33.66	98.50	76.10
4	BEL22	0.59	8.17	31.04	79.83	54.42
5	EU202	0.42	4.27	34.49	51.67	177.89
6	BEL36	0.12	7.02	29.56	49.50	69.06
7	YS203	0.04	11.22	30.76	53.33	70.45
8	CR102	-0.95	6.86	36.88	57.33	61.27
9	ORO9	-1.20	11.15	25.55	61.17	50.15
10	KD102	-1.22	4.78	34.31	51.17	68.70
11	EN103	-1.38	5.67	36.47	56.33	77.40
12	OCJ2	-2.06	8.43	28.17	50.50	58.48

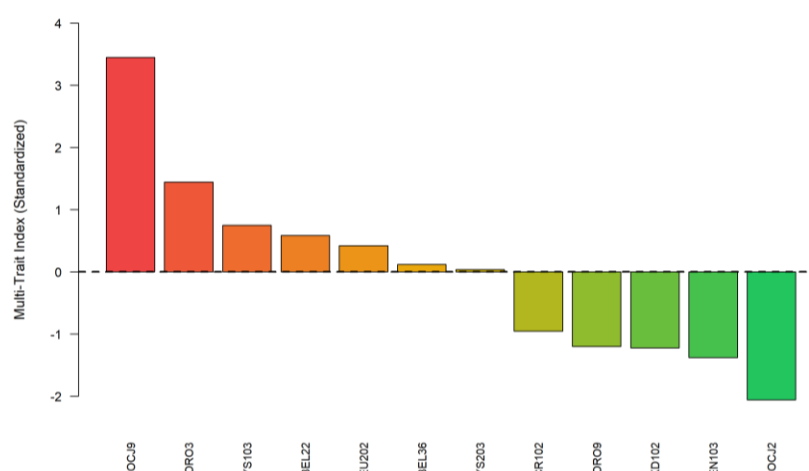


Figure 5: Multi-Trait Performance Index Ranking of Cashew Clones for Selection

Discussion

The twelve clones evaluated in this study showed clear and consistent genetic variation across all measured trait groups, confirming the value of the CRIN germplasm collection as a source of diversity for cashew improvement in Nigeria. Nut weight ranged from 4.27 g (EU202) to 11.34 g (OCJ9), and kernel weight from 1.50 g (EU202) to 3.75 g (OCJ9). These values are in line with ranges reported across Nigerian ecologies and multi-location trials (Adeniyi and Nduka 2022; Aliyu et al., 2014). The very high positive correlations among nut weight, kernel weight, and nut length ($r > 0.96$) confirm that selecting for any one of these traits will improve the others at the same time, a pattern that has been consistently documented in cashew germplasm evaluations (Rossetti et al., 2020; Aliyu and Awopetu, 2011).

Shelling percentage showed the expected negative relationship with nut size ($r = -0.719$), reflecting the well-known biological trade-off between absolute nut size and proportional kernel recovery (Aliyu and Awopetu, 2011). However, absolute kernel mass remains most important commercially. The large-nutted clones (OCJ9, YS203, and ORO9) consistently produced the heaviest kernels, supporting the view that total kernel weight per nut matters more than shelling percentage alone in determining economic value (Bello et al., 2019). This negative correlation ($r = -0.719$) specifically indicates that larger nuts possess disproportionately thicker and heavier shells relative to their total nut mass, which reduces the proportion of recoverable kernel during industrial processing. In practical terms, although OCJ9 and YS203 yield the heaviest absolute kernels, their lower shelling percentages (33.78% and 30.76%, respectively) mean that a greater share of nut mass is occupied by shell material. This has direct implications for industrial kernel recovery efficiency: processing facilities handling large-nutted material may incur higher shelling costs per unit of kernel output. Breeders should therefore consider selecting for an optimal shell thickness independently of nut size to improve industrial processing efficiency without sacrificing kernel yield.

Reproductive traits (pollen tube length and germination percentage) varied independently of nut quality, with only weak or very small correlations observed. This independence is useful for breeding because it allows improvement of pollen vigor and therefore fruit set, without losing gains in kernel size or recovery. This agrees with observations in hybrid seedling trials where reproductive vigor and nut traits could be selected together (Kadjo et al., 2025). Clones such as EU202 (longest pollen tubes), ORO3, and YS103 (highest germination) are valuable genetic resources for bringing superior pollen performance into breeding populations, especially in environments where pollination efficiency limits yield stability.

Morphological characterization showed further diversity in tree habit, leaf shape, young leaf colour, apex form, and leaf size. The negative correlation between leaf size and both nut weight and kernel weight ($r \approx -0.53$) points to a possible resource allocation pattern, where clones with smaller leaves may direct more photosynthates toward reproductive structures. This is consistent with the general principle of source-sink competition in perennial tree crops (Wardlaw, 1990), and is supported by evidence in cashew germplasm where reduced vegetative partitioning was linked to greater reproductive output (Dadzie et al., 2014).

However, this requires further investigation with direct measurements of carbon partitioning before firm conclusions can be drawn.

Principal component analysis effectively separated the main size-efficiency trade-off axis (PC1) from the independent reproductive vegetative axis (PC2), confirming multi-dimensional genetic diversity within the collection. The multi-trait performance index, which brought together nut quality, pollen performance, and vegetative traits, ranked OCJ9 highest overall (index = 3.45), driven by its large nut weight (11.34 g), the highest kernel weight (3.75 g), acceptable shelling, and good pollen traits. ORO3 (index = 1.44) and YS103 (index = 0.75) ranked second and third, with excellent reproductive performance that would improve fruit set when used as parents. These well-rounded clones are likely to perform more consistently under varying field conditions than single-trait specialists, in line with earlier multi-trait stability reports in cashew (Aliyu et al., 2014; Bello et al., 2019).

The independence of reproductive traits from nut quality, together with the clear multi-dimensional variation captured by PCA, shows that it is possible to improve kernel yield, fruit set, and canopy efficiency together without the severe trade-offs often seen in perennial crop breeding as long as selection targets traits that are either positively correlated or uncorrelated. OCJ9 stands out as a key parent for future crosses. ORO3 and YS103 offer complementary pollen vigor that could be used to improve yield stability across diverse Nigerian agro-ecologies. Clone OCJ9 merits particular attention in future hybrid breeding programs across West Africa. Its outstanding morphological architecture, characterized by the largest nut dimensions (length 3.79 cm, width 2.99 cm, girth 1.84 cm), the heaviest kernel (3.75 g), and an upright and open tree habit that facilitates canopy light interception, makes it an ideal donor parent for transmitting large nut size and high kernel weight to hybrid progeny. When crossed with clones possessing superior pollen performance such as ORO3 (germination 98.00%, pollen tube length 133.33 μ m) and YS103 (germination 98.50%), OCJ9-derived hybrids could potentially combine high kernel yield with enhanced fruit set and yield stability. Given the diversity of agro-ecological zones across West Africa (humid forest, derived savanna, and Guinea savanna), multi-environment testing of OCJ9-based hybrids would be necessary to confirm the stability of its large-nut trait expression under varying rainfall and temperature regimes. Its use as a recurrent parent in backcross programs could accelerate the development of improved varieties suited to the Nigerian and broader West African cashew industry.

Conclusion

This multi-trait evaluation of twelve cashew clones has shown substantial genetic variation and clear opportunities for simultaneous improvement of nut quality, reproductive efficiency, and vegetative traits. OCJ9 emerged as the top clone, combining the largest nuts (11.34 g), the highest kernel weight (3.75 g), and solid pollen performance. ORO3 and YS103 offer complementary strengths in pollen vigour and germination that will help improve fruit set in future crosses. The independence of reproductive traits from nut quality and the multi-dimensional diversity captured by PCA confirm that balanced, high-performing varieties can

be developed without the usual trade-offs, provided selection is directed toward traits that are positively correlated or genetically independent.

Future Research Direction

Future research should focus on validating the performance of the top-ranked clones, OCJ9, ORO3, and YS103 across diverse West African agro-ecologies through multi-environment trials designed to assess genotype-by-environment interaction and confirm trait stability under varying rainfall, temperature, and soil conditions. Alongside this, controlled hybridization programs should be initiated, specifically crossing OCJ9 with high-performing pollen donors such as ORO3 and YS103, to develop and evaluate F1 hybrid progeny that combine the large nut size and high kernel weight of OCJ9 with the superior reproductive efficiency of its cross partners.

Further work is also needed to directly measure shell thickness and shell density across large- and small-nutted clones, which would provide a clearer morphological explanation for the observed size-efficiency trade-off and its practical consequences for industrial kernel recovery. At the molecular level, marker-assisted analysis of the genetic architecture underlying the independence between nut quality and pollen performance traits would help identify favorable alleles that breeders can pyramid efficiently into improved populations. Finally, investigation of carbon partitioning patterns in contrasting clones would help clarify the physiological mechanisms that link canopy architecture, particularly leaf size and tree habit, with nut yield and reproductive output, providing a stronger biological basis for selection decisions in future cashew improvement programs.

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