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Evaluation of growth performance of cashew (*Anacardium occidentale* L.) hybrid seedlings using vegetative traits

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Abstract: This study evaluated the vegetative vigor of twenty hybrid families derived from a diallel cross among five cashew genotypes (KK36, W9, TPTO2, N1 and YKKF1) under nursery conditions in Côte d'Ivoire. Ten growth parameters were assessed including seedling height, number of branches, number of leaves and other indicators of vegetative vigor. The experiment lasted six months with measurements conducted monthly and final data collected at 180 days, a critical stage for transplantation and future yield potential. Significant differences ($p < 0.001$) were observed among hybrids for all traits evaluated. The hybrids N1×W9, W9×KK36, KK36×N1 and W9×N1 displayed the longest germination times (12 days), whereas TPTO2×N1 germinated fastest (9 days). W9×KK36 and KK36×W9 exhibited the highest number of branches, while KK36×N1 had the greatest branch length. N1×W9 produced the tallest seedlings; TPTO2×W9 showed the longest leaves and TPTO2×KK36 had the widest east-west wingspan. Positive correlations were found between seedling height and circumference and between number and length of branches. Principal Component Analysis grouped vigor-related traits into two major categories: one related to seedling architecture (height, number and length branch and north-south wingspan) and the other to leaves dimensions. Based on a vigor index, hybrids were classified into three performance groups: high-performing (primarily with KK36 as the female parent), intermediate-performing (with W9 and TPTO2 as female parents) and low-performing (with YKKF1 and N1 as female parents). These results support early-stage seedling evaluation as an effective strategy for reducing planting density and identifying high-performance hybrids likely to give better yields at maturity.

Keywords: cashew breeding, vigor index, hybrid families, morphological traits, nursery.

Abbreviations: GT_Germination time; NB_Number of branches; LB_Length of branches; HS_Height of seedling; SC_Seedling circumference; LL_Leaf length; LW_Leaf width; NL_Number of leaves; EWSW_East-west seedling wingspan and NSSW_North-south seedling wingspan.

Introduction

The cashew tree (*Anacardium occidentale* L.) is a diploid dicotyledonous plant with a chromosome number of 2n=42 (Aliyu and Awopetu, 2007). Native to northeastern Brazil, cashew was introduced to tropical regions worldwide by the Portuguese in the 16th century for soil conservation purposes (Salam and Peter, 2010). Today cashew trees are widely cultivated for their edible nuts which are rich in fats and proteins (Chen et al., 2023). In addition, the liquid extracted from cashew nut shells known as CNSL (Cashew Nut Shell Liquid) is highly valuable and extensively used in various industrial applications (Nyirenda et al., 2021; Roy et al., 2022).

Cashew cultivation plays a significant role in the socio-economic development of many countries around the world (Dendena and Corsi, 2014; Ingram et al., 2015). It has emerged as a fast-growing cash crop offering numerous export opportunities for African nations (Dedehou et al., 2015). West Africa alone accounts for approximately 45% of global cashew nut production, with Côte d'Ivoire, Ghana, and Nigeria being the leading producers (Monteiro et al., 2017). Since 2015, Côte d'Ivoire has become the world's top producer and exporter of cashew nuts reaching nearly one million tons by 2021 (FIRCA, 2022). This achievement is primarily due to the expansion of cultivated land which increased from 500,000 hectares in 2006 to approximately 1,350,000 hectares in 2018 (FIRCA, 2018). Nevertheless, despite its leading position Côte d'Ivoire faces low orchard yields averaging between 350 and 500 kg/ha (Dadzie et al., 2014), compared to 1,000 to 1,500 kg/ha in countries such as India, Vietnam and Brazil (Rege and Lee, 2022). The low productivity of cashew plantations in Côte d'Ivoire is mainly attributed to the lack of improved varieties, leading to reliance on unselected and readily available planting material. As a result, enhancing key traits such as yield nut quality and resistance to pests and diseases remains a pressing necessity (Kouakou et al., 2018; Kouakou et al., 2020).

Improving global food and nutritional security (Mackay et al., 2021) requires innovative plant breeding strategies. One effective approach involves crossing genetically distinct cashew genotypes to produce hybrids that express desirable traits. The development of hybrid varieties is especially crucial for cashew a crop characterized by high levels of cross-pollination. However, only a few countries have reported the successful development of high-performing hybrid cashew varieties (Sethi et al., 2016; Eradasappa et al., 2020). Tanzania remains the only African country to have effectively created, evaluated and disseminated new hybrid cashew varieties (Masawe, 2006; Masawe and Kapinga, 2016; Masawe and Kapinga, 2017). These hybrids demonstrate heterosis (hybrid vigor) which can be exploited through clonal propagation at any stage of the breeding program (Eradasappa et al., 2020).

The breeding process in cashew is inherently complex due to the species' perennial nature and extended juvenile phase (Syed et al., 2005; Savadi et al., 2020). Cashew improvement demands substantial land area prolonged, evaluation periods and intensive labor making the selection of improved varieties a long, costly and labor-intensive undertaking. To mitigate these constraints juvenile traits may be used for early identification and preselection of superior genotypes thereby shortening the selection cycle (Akpertey et al., 2017). In Côte d'Ivoire, the initial step in varietal improvement involved the selection of 209 high-potential trees (Kouakou et al., 2020). These genotypes provided a valuable reservoir of genetic variation from which several hybrid combinations were derived.

This study evaluates the growth vigor of 20 cashew hybrid families based on vegetative traits. The main objectives were to compare the performance of hybrid seedlings originating from different parental crosses and to assess the influence of parental genetic combinations on the growth dynamics of the hybrids. This research highlights promising hybrid combinations for inclusion in future cashew breeding programs. The results offer valuable guidance for researchers and breeders in selecting both parental genotypes and hybrids thereby contributing to improved cashew nut productivity through more efficient varietal development.

Results

Growth curve of hybrid seedlings

The growth curves of the hybrid seedlings are presented in Figure 1. The number of branches increased with age across all hybrid families, although certain combinations exhibited more pronounced growth (Fig. 1a). The hybrids W9×KK36 and KK36×W9 showed a faster increase in number of branches after 60 days indicating superior branching ability whereas the hybrid TPTO2×KK36 recorded the lowest number of branches suggesting a less bushy architecture. In contrast, TPTO2×N1, YKKF1×W9 and YKKF1×N1 exhibited no branching on their stems. Height growth was particularly notable for certain hybrids especially N1×W9 and N1×KK36 which achieved greater heights by day 90 compared to other families (Fig. 1b). The families KK36×N1 and KK36×W9 displayed slower vertical growth throughout the period and remained the shortest. The stem girth of the seedlings increased with age indicating structural reinforcement (Fig. 1c). The hybrid N1×KK36 exhibited the largest stem circumference from day 90 onward while most other families showed moderate growth. Conversely, the hybrids YKKF1×N1 and YKKF1×TPTO2 had the thinnest stems. The increase in number of leaves was consistent across all hybrid families (Fig. 1d). The hybrids TPTO2×W9 and TPTO2×YKKF1 exhibited the highest leaf counts after 180 days. In contrast, KK36×W9 and YKKF1×KK36 showed the most limited leaf development. The east-west wingspan of the seedlings varied with the age of the hybrid families (Fig. 1e). The hybrid N1×W9 showed the widest east–west wingspan at 30, 60 and 90 days while TPTO2×KK36 reached the maximum wingspan at 180 days. Meanwhile, YKKF1×TPTO2 and YKKF1×N1 exhibited the least expansion over time. With respect to the north-south wingspan of the hybrid families, the growth curves followed similar trends from day 30 to 90 (Fig. 1f). However, after 90 days, KK36×N1 displayed rapid expansion attaining the widest north-south wingspan at 180 days. Conversely, YKKF1×N1 consistently exhibited the slowest growth at all stages.

Growth performance

The mean values of the traits measured on the hybrid seedlings are presented in Table 1. Analysis of variance revealed a highly significant difference ($p < 0.001$) among hybrid families for all ten traits evaluated. A comparison of the mean values showed that N1×W9, W9×KK36, KK36×N1 and W9×N1 exhibited the longest germination time **(**12 days) whereas the TPTO2×N1 family had the shortest (9.8 days). W9×KK36 and KK36×W9 hybrids recorded the highest number of branches (2.0 and 2.2 respectively) while TPTO2×KK36 produced the fewest (0.3 branches). However, the KK36×N1 hybrid had the longest average branch length (6.90 cm) whereas TPTO2×KK36 exhibited the shortest (0.82 cm). The hybrid families TPTO2×N1, YKKF1×W9 and YKKF1×N1 also exhibited a complete absence of branching in their seedlings. However, KK36×N1 hybrid showed the longest branch length (6.90 cm) while TPTO2×KK36 had the shortest (0.82 cm). The average seedling height indicated that the N1×W9 hybrid was the tallest (38.69 cm) whereas KK36×N1 and KK36×W9 were the shortest (24.90 cm and 24.93 cm respectively). Regarding stem circumference, N1×KK36 recorded the largest stem circumference (13.04 mm) while YKKF1×N1 had the smallest (9.83 mm)**.** Leaf length ranged from 14.07 cm to 18.54 cm with TPTO2×W9 exhibiting the longest leaves and KK36×N1 the shortest. However, W9×YKKF1 had the widest leaves (5.52 cm) while YKKF1×KK36 showed the narrowest (4.35 cm). In terms of the number of leaves, TPTO2×W9 and TPTO2×YKKF1 produced the highest values (21.3 and 21.8 respectively), while KK36×W9 had the lowest (14.9). With respect to seedling wingspan, TPTO2×KK36 had the widest east-west wingspan (27.91 cm) whereas YKKF1×N1 recorded the smallest (17.19 cm). The KK36×N1 hybrid had the greatest north-south wingspan (27.12 cm) while YKKF1×N1 exhibited the smallest (17.00 cm).

Correlation studies

The Pearson correlation test revealed significant positive correlations among vegetative traits at the $p < 0.001$ level (Fig. 2). The number of leaves was significantly correlated with leaf length while leaf length was positively associated with leaf width**.** Germination time showed correlations with both number of branches and branch length. Moreover, number of branches exhibited a strong positive correlation with branch length. Seedling height was positively correlated with leaf dimensions and with east-west wingspan. Finally, stem circumference was positively correlated with leaf width**,** seedling wingspan and seedling height**.**

Table 1. Mean ± standard deviations of the performances of the twenty cashew hybrid families for the traits studied.

Hybrid Families	GT (days)	NB	LB (cm)	HS (cm)	SC (mm)	LL (cm)	LW (cm)	NL	EWSW (cm)	NSSW (cm)
N1×TPTO2	10.8±1.55^{b}	0.7±1.06^{cd}	1.59±2.13^{cd}	36.21±1.42^{ab}	12,86±0.16^{ab}	15.27±0.77^{bc}	5.12±0.61^{b}	17.5±1.08^{bc}	23.47±1.42^{ab}	23.71±2.71^{ab}
N1×W9	12.0±1.05^{a}	1.3±1.57^{c}	3.31±3.31^{bc}	38.69±4.84^{a}	12.22±0.97^{ab}	15.95±1.48^{bc}	5.02±0.54^{b}	19.7±1.06^{ab}	26.46±5.89^{ab}	19.95±3.87^{c}
N1×KK36	11.0±1.33^{ab}	0.4±1.26^{de}	1.33±4.21^{cd}	37.97±2.84^{ab}	13.04±0.72^{a}	16.98±0.93^{ab}	5.20±0.60a^{b}	20.3±1.06^{ab}	22.81±3.09^{ab}	22.37±3.72^{ab}
YKKF1×N1	10.2±0.79^{b}	-	-	26.17±2.89^{cd}	9.83±0.99^{d}	15.28±0.99^{bc}	4.78±0.46^{bc}	18.8±1.62^{ab}	17.19±2.72^{c}	17.08±2.78^{d}
YKKF1×KK36	10.3±1.70^{b}	0.9±1.10^{cd}	4.89±6.03^{ab}	30.11±5.92^{c}	10.76±1.64^{c}	16.74±2.35^{ab}	4.35±0.47^{c}	15.3±2.75^{d}	20.43± 3.97^{b}	21.34±2.98^{bc}
YKKF1×TPTO2	10.7±1.16^{b}	0.4±0.52^{de}	2.98±3.86^{c}	30.70±6.01^{c}	10.86±1.65^{c}	17.39±1.06^{ab}	4.95±0.52^{bc}	17.4±1.71^{bc}	17.56±3.35^{b}	20.86±6.20^{bc}
YKKF1×W9	10.3±1.49^{b}	-	-	29.32±4.48^{cd}	10.79±1.52^{c}	16.46±1.37^{b}	4.93±0.43^{bc}	17.00±2.00^{c}	19.01±2.49^{b}	20.51±4.23^{bc}
W9×KK36	12.0±0.67^{a}	2.0±1.63^{ab}	5.81±3.38^{ab}	33.60±2.37^{ab}	12.05±0.72^{ab}	16.81±2.19^{ab}	5.06±0.41^{b}	17.8±1.13^{bc}	24.28±2.67^{ab}	21.58±3.24^{bc}
TPTO2×KK36	10.3±0.82^{b}	0.3±0.67^{e}	0.82±1.74^{d}	34.27±7.55^{ab}	12.01±1.08^{bc}	16.99±1.23^{ab}	4.97±0.49^{bc}	17.2±3.36^{bc}	27.91±5.34^{a}	21.72±3.02^{bc}
TPTO2×W9	10.9±1.66^{b}	1.2±1.03^{c}	5.81±4.46^{ab}	33.12±3.27^{b}	11.49±0.79^{bc}	18.54±1.16^{a}	5.30±0.42^{ab}	21.3±1.49^{a}	23.12±2.04^{ab}	22.39±5.36^{ab}
KK36×N1	12.0±0.00^{a}	1.7±1.64^{ab}	6.90±5.48^{a}	24.90±3.45^{d}	11.91±1.63^{b}	14.07±0.84^{d}	4.88±0.54^{bc}	17.8±0.63^{bc}	18.52±2.11^{b}	27.12±1.49^{a}
W9×N1	12.0±0.00^{a}	1.5±0.97^{b}	4.67±2.81^{b}	29.16±2.62^{cd}	12.15±0.67^{ab}	16.83±1.29^{ab}	5.32±0.56^{ab}	18.5±1.35^{ab}	22.36±2.85^{ab}	22.33±2.55^{ab}
TPTO2×N1	9.8±1.40^{b}	-	-	28.77±4.87^{cd}	11.89±0.80^{b}	15.75±1.84^{bc}	4.92±0.45^{bc}	18.0±1.94^{b}	24.61±2.55^{ab}	21.54±1.77^{bc}
N1×YKKF1	10.0±1.05^{b}	0.4±0.70^{de}	1.93±3.19^{cd}	30.65±1.73^{c}	11.74±0.64^{bc}	14.96±0.61^{c}	4.93±0.48^{bc}	15.8±0.92^{cd}	21.27±1.40^{ab}	22.71±2.76^{ab}
KK36×TPTO2	10.2±0.78^{b}	1.6±1.26^{ab}	4.19±3.21^{b}	31.27±3.83^{c}	11.80±0.59^{b}	14.98±0.72^{c}	4.83±0.59^{bc}	15.4±1.35^{cd}	22.21±1.35^{ab}	19.55±2.76^{cd}
KK36×W9	11.1±0.74^{ab}	2.2±1.62^{a}	5.11±3.26^{ab}	24.93±5.13^{d}	12.16±1.07^{ab}	14.17±1.05^{cd}	4.59±0.45^{bc}	14.9±2.02^{e}	24.05±2.40^{ab}	24.08±1.84^{ab}
KK36×YKKF1	10.2±0.42^{b}	0.6±0.84^{d}	3.16±4.22^{bc}	32.88±4.35^{bc}	11.60±0.98^{bc}	15.87±1.10^{bc}	5.23±0.18^{ab}	16.6±1.43^{cd}	22.36±1.12^{ab}	21.75±2.67^{bc}
TPTO2×YKKF1	10.3±1.77^{b}	0.4±0.84^{de}	1.22±2.62^{cd}	33.50±3.86^{ab}	11.51±1.40^{bc}	15.95±1.12^{bc}	5.10±0.26^{b}	21.8±2.04^{a}	21.53±2.09^{ab}	21.96±4.85^{bc}
W9×TPTO2	11.0±0.00^{b}	0.8±1.14^{cd}	2.76±3.92^{c}	33.78±3.09^{ab}	12.50±0.67^{ab}	17.96±0.63^{ab}	5.45±0.36^{ab}	18.0±1.83^{b}	22.38±4.34^{ab}	21.05±4.35^{bc}
W9×YKKF1	10.4±0.84^{b}	0.5±0.53^{de}	3.62±4.48^{b}	34.37±3.16^{ab}	11.43±1.04^{bc}	18.21±1.80^{ab}	5.52±0.53^{a}	19.1±2.47^{ab}	20.88±2.14^{ab}	21.34±2.98^{bc}
F	4.768	4.117	3.589	8.663	5.042	9.169	3.372	11.26	8.204	2.991
P	< 0.001***	< 0.001***	< 0.001***	< 0.001***	< 0.001***	< 0.001***	< 0.001***	< 0.001***	< 0.001***	< 0.001***

*** P highly significant,Means followed by the same letter in the same column are identical at the 5% probability level. Germination time (GT), Number of branches (NB), Length of branches (LB), Height of seedling (HS), Seedling circumference (SC), Leaf length (LL), Leaf width (LW), Number of leaves (NL), East-west seedling wingspan (EWSW) and North-south seedling wingspan (NSSW).

Table 2. Principal components of vegetative characteristics of cashew hybrid families.

Principal components	PC1	PC2	PC3	PC4	PC5
Eigenvalue	3.21	2.87	1.36	0.93	0.63
Percentage of variance	32.08	28.69	13.59	9.30	6.28
Cumulative percentage of variance	32.08	60.77	74.36	83.65	89.94
Vegetative traits					
GT	0.81	0.09	0.28	-0.29	0.23
NB	0.94	-0.11	0.18	-0.20	0.03
LB	0.81	-0.08	0.49	0.00	-0.15
HS	-0.06	0.88	-0.15	-0.22	-0.01
SC	0.60	0.49	-0.48	0.12	-0.09
LL	-0.29	0.68	0.49	-0.10	-0.24
LW	-0.08	0.78	0.29	0.21	-0.30
NL	-0.20	0.63	0.30	0.26	0.63
EWSW	0.34	0.55	-0.47	-0.28	0.06
NSSW	0.64	0.03	-0.15	0.74	-0.04

Germination time (GT), Number of branches (NB), Length of branches (LB), Height of seedling (HS), Seedling circumference (SC), Leaf length (LL), Leaf width (LW), Number of leaves (NL), East-west seedling span (EWSS) and North-south seedling span (NSSS).

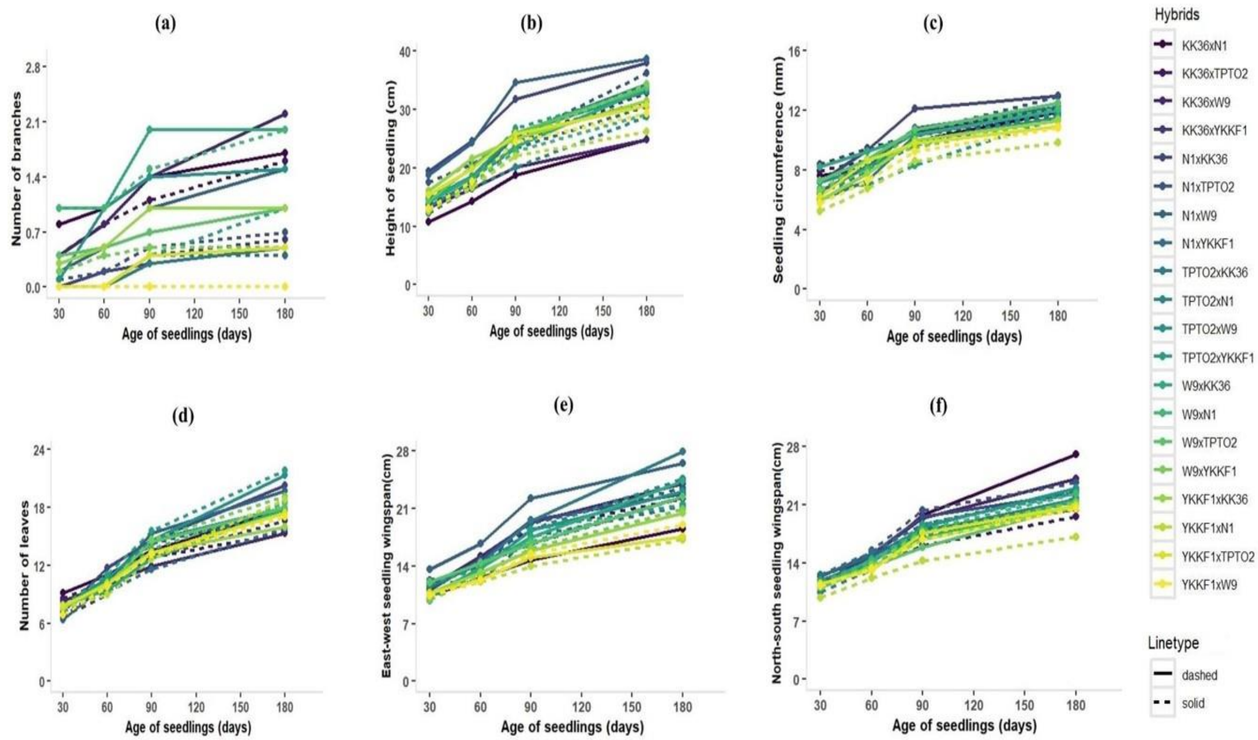

Fig. 1 Growth curve for hybrids as a function of seedling age; (a) number of branches curve; (b) height curve; (c) stem circumference curve; (d) number of leaves curve; (e) east-west wingspan curve; (f) north-south wingspan curve.

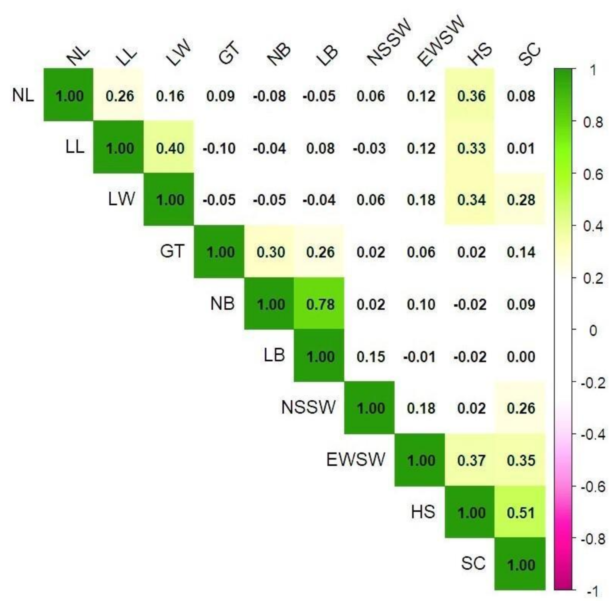

Fig. 2 Diagonally graphical representation of correlation coefficients for vegetative traits in cashew hybrids seedling.

Table 3. Agromorphological and agronomic characteristics of the five selected parental genotypes used in hybridization.

Parents' code	Average yield (nuts kg /tree/year) over 4 to 5 years of observation	Average nut size or graining (number of nuts/kg)	Percent of mean kernel content (%)	Behavior towards the main cashew diseases and pests
KK36	20.52	136	26.7	Susceptible to anthracnose and *Helopeltis sp* but tolerant to bacteriosis
W9	11.5	103	27.0	Susceptible to anthracnose and bacteriosis, but tolerant to *Helopeltis sp*
TPTO2	14.3	105	28.2	Susceptible to bacteriosis, but tolerant to anthracnose and *Helopeltis sp*
N1	35.75	184	28.8	Tolerant to anthracnose and *Helopeltis sp,* but susceptible bacteriosis
YKKF1	23.8	206	31.1	Tolerant to anthracnose and bacteriosis, but susceptible to *Helopeltis sp*

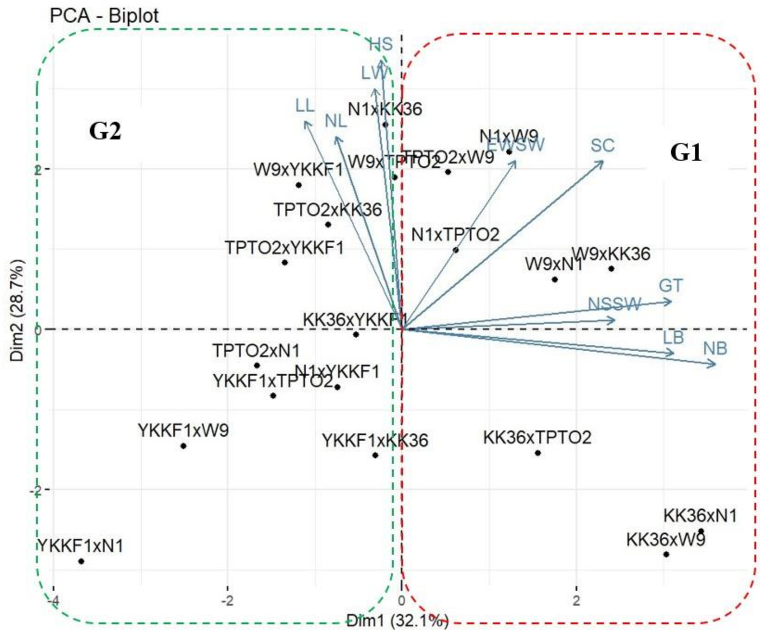

Fig. 3 Graphical representation of parameters and individuals on planes 1–2 of PCA.

Table 4. List of morphological traits related to the vigor of cashew hybrid seedlings analyzed and method of measurement.

Number	Traits (unit)	Codes	measurement approaches
1	germination time (day)	GT	Count the number of days between sowing the nut and the emergence of the seedling
2	Number of branches (count)	NB	Count the total number of branches observed on each seedling
3	length of branches (cm)	LB	Measure the length of all the branches on the seedling
4	Height of seedling (cm)	HS	Measuring seedling height
5	Seedling circumference (mm)	SC	Measure thickness of main stem of seedling
6	Leaf length (cm)	LL	Measure length of 10 leaves located at different levels on seedling
7	Leaf width (cm)	LW	Measure width of 10 leaves located at different levels on seedling
8	Number of leaves (count)	NL	Count total leaves on seedling
9	East-west seedling wingspan (cm)	EWSW	Measure the distance between the two terminal leaves of the seedling, on the east-west side
10	North-south seedling wingspan (cm)	NSSW	Measure the distance between the two terminal leaves of the seedling, on the north-south side

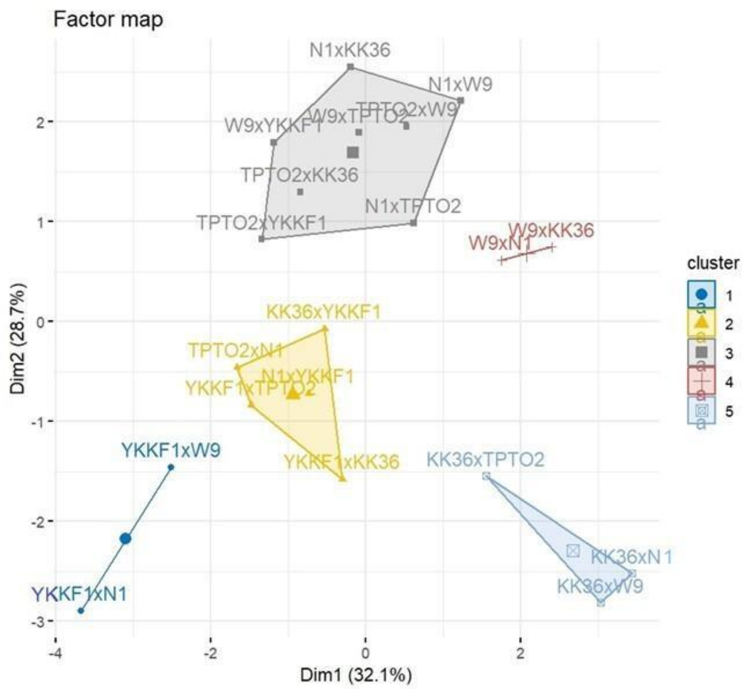

Fig 4. The hierarchical clustering analysis (HCA) of 20 cashew hybrids based on the vegetative traits.

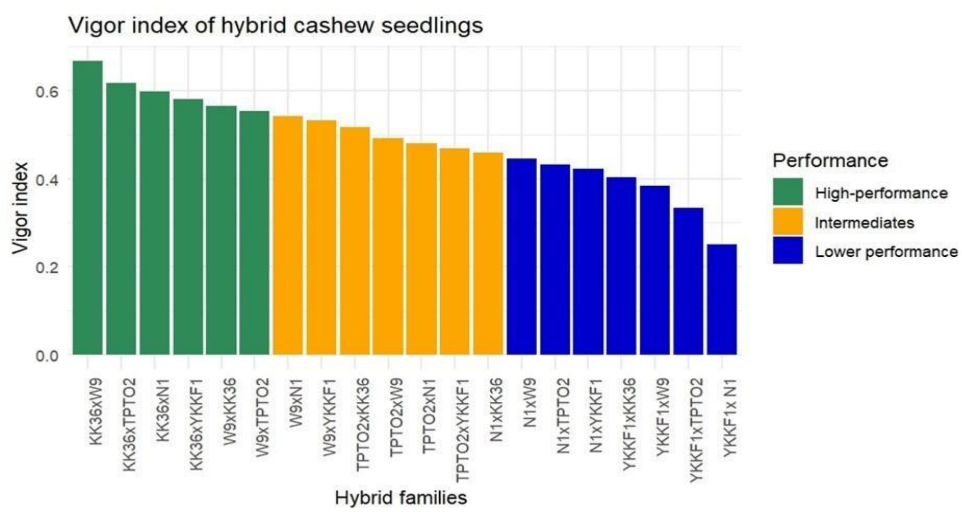

Fig. 5 Histogram of seedling *Vigor index of hybrid cashew seedling families grouped by performance class.*

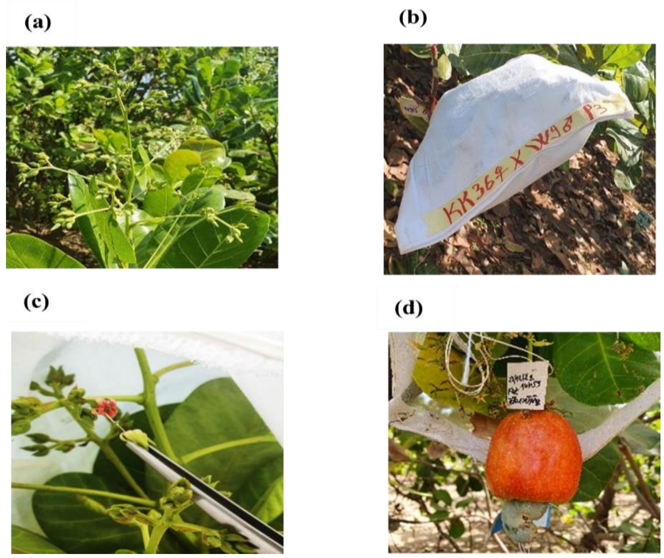

Fig. 6 Stages of the manual hybridization process in cashew (*Anacardium occidentale* L.)**;** (**a)** healthy cashew panicle, (**b)** panicle bagged with organza bag, (**c)** manual pollination and **(d)** mature cashew fruit from manual pollination.

Principal Component Analysis and Classification

Principal Component Analysis (PCA) revealed that the first three components had eigenvalues greater than one (Table 2). The first two components accounted for 60.77% of the total variation among hybrid families. These axes were retained for further analysis in accordance with Kaiser's criterion (Kaiser, 1958). The first principal component (PC1) accounted for 32.08% of the total variance and was primarily associated with germination time**,** number and length of branches, seedling circumference and north-south wingspan as indicated by the color gradient in Figure 3. This component represents the architectural traits of the hybrid seedlings. The second principal component (PC2) explained 28.69% of the total variance and was mainly attributed to height of seedling, leaf traits and east-west wingspan. It reflects the foliar size dimension of the cashew seedlings. The representation of individuals on the factorial plane 1-2 of the PCA (Fig. 3) highlights along axis 1, two main groups: Group I (GI) includes hybrids characterized by a high number and length of branches, large stem circumference, early germination and broad canopy development whereas Group II (GII) consists of tall hybrids with well-defined leaf dimensions.

The graphical representation of the 20 hybrid families analyzed on the hierarchical cluster analysis (HCA) plane (F1–F2) is illustrated in Figure 4. The projection of the hybrids onto the two principal axes enables the classification of these 20 hybrid families into five distinct groups. In conjunction with Figures 4 and 5, the first group located at the negative end of both axis 1 and axis 2 comprises two hybrid families (YKKF1×W9 and YKKF1×N1). Hybrids within this group are characterized by low values for number and length of branches. The second group comprising five hybrid families YKFF1×TPTO2, YKKF1×KK36, TPTO2×N1, KK36×YKKF1 and N1×YKKF1 is situated in the negative region of axis 2. Seedlings in this group exhibit reduced height along with small leaf dimensions (NL, LL and LW). The third group is positioned in the positive region of axis 2 and includes eight hybrid families: N1×KK36, N1×W9, TPTO2×W9, W9×TPTO2, W9×YKKF1, TPTO2×KK36, TPTO2×YKKF1 and N1×TPTO2. These families are distinguished by high values for height of seedling and all leaf-related parameters (NL, LL and LW). The fourth group comprising the W9×N1 and W9×KK36 hybrid families is located in the positive quadrant of both axis 1 and axis 2. These hybrids are marked by a large seedling circumference and a wide east-west wingspan. Lastly, the fifth group situated at the positive end of axis 1 includes the KK36×TPTO2, KK36×N1 and KK36×W9 families. This group is characterized by a high number and length of branches and a prolonged germination time.

Index Vigor

The histogram in Figure 5 illustrates the vigor index of cashew seedlings across the different hybrid families. Three performance groups were identified: high performance (green), intermediate performance (orange) and low performance (blue). The first group characterized by high performance displays the highest vigor indices exceeding 0.55. Hybrids with KK36 as the female parent exhibited the highest values followed by the hybrids W9×KK36 and W9×TPTO2. The second group comprising hybrids with intermediate performance had vigor index values between 0.4 and 0.5. This group includes families with TPTO2 as the female parent as well as the hybrid families W9×N1, W9×YKKF1 and N1×KK36. The third group includes hybrid families with the lowest vigor indices generally below 0.4. These are hybrids with YKKF1 and N1 as female parents with the exception of the N1×KK36 hybrid.

Discussion

Early identification of agronomic performance in perennial crops is a crucial challenge for the efficiency of genetic improvement programs. In cashew traits measured at the seedling stage can provide valuable insights into the future potential of adult trees in terms of yield. Characteristics such as seedling height, number of branches, stem circumference, wingspan and number of leaves are directly related to vegetative vigor a key factor for rapid growth. These traits are considered indirect predictors of productivity as they influence the photosynthetic surface and plant architecture, thereby promoting earlier fruiting (Mog and Nayak, 2018). This methodological approach has been applied in other species as well. For instance, Teixeira et al. (2012) demonstrated that in coffee seedlings with greater nursery vigor particularly longer primary plagiotropic branches developed favorable architecture and higher grain yield. Similarly, Atay and Koyuncu (2022) found that in apple trees, seedling height, branching and leaf area were good indicators of fruiting potential at maturity. In rubber tree studies, Gonçalves and Marques (2014) confirmed that selecting clones with larger stem circumference at the seedling stage reduced the non-productive phase of plantations, while ensuring vigorous development and higher latex yield at maturity.

In the present study, hybrid seedlings obtained through the crossing of elite parents exhibited differing growth trajectories depending on seedling age. Most hybrids showed distinct growth patterns as early as 90 days after sowing. This early phenotypic variability may be attributed to heterosis effects, resulting from favorable genetic combinations between parental genotypes. Certain hybrid combinations appear to express vigor earlier than others, indicating rapid morphological differentiation that may confer an adaptive advantage during the initial developmental stages. These findings are consistent with the work of Paques (2009), who demonstrated that hybrid progenies of larch (*Larix decidua* × *Larix kaempferi*) displayed superior vigor within the first weeks of growth.

The analysis of morphological traits across different hybrid families revealed significant variation, highlighting a genetic diversity that can be leveraged in breeding programs. Among the most discriminating traits, leaf surface area and wingspan stood out due to their direct influence on productivity. These parameters are recognized as key indicators of vegetative vigor and yield potential in perennial species. Our findings align with those of Mog et al. (2019), who showed that increased leaf area in cashew is positively correlated with earlier flowering greater production of floral panicles bearing perfect flowers and ultimately higher nut yields. In this context, the TPTO2×W9 hybrid, which exhibited high values for leaf number, leaf width and wingspan represents a promising candidate for early selection aimed at yield improvement. Furthermore, canopy architecture particularly its distribution along the north-south plays a decisive role. The KK36×N1 family characterized by a broader north-south wingspan may be advantageous for yield optimization. Indeed, Adu-Gyamfi et al. (2022) demonstrated that greater north-south wingspan enhances light interception and improves early nut yield. These findings suggest that certain morphological traits observable as early as the seedling stage may serve as reliable indicators of adult tree performance.

A significant positive correlation was observed between the number and length of branches. A denser and more extended branching pattern may enhance the plant's capacity to develop a larger foliar system, thereby increasing the available photosynthetic surface. This is particularly beneficial for perennial crops such as cashew where a well-developed canopy is essential to maximize light interception, encourage better flowering, and potentially result in higher nut yields as previously demonstrated by Wu et al. (2015) and Adu-Gyamfi et al. (2020) in their studies on cashew. Likewise, the strong positive correlation observed between leaf number and leaf size is a key indicator of enhanced photosynthetic capacity in seedlings. A greater total leaf surface, resulting from the interaction between quantity and size, improves light capture and biomass production thereby promoting better seedling growth. Franco et al. (2006) notably emphasized the importance of vigorous foliar development at the nursery stage for successful establishment and optimal growth after transplanting.

Principal component analysis (PCA) revealed that the measured parameters could be grouped into two main components accounting for 60.77% of total variability. The first principal component reflects hybrid seedling architecture. In this regard, Grossnickle and MacDonald (2018) stressed that seedling architecture is a critical determinant of early vigor. The second principal component corresponds to leaf size an indicator of seedling health, vigor and adaptability after transplanting. Well-developed leaves are often associated with increased photosynthesis, faster growth and greater stress tolerance. The vigor index proved to be a relevant indicator of cashew seedling productivity. Hybrids involving female parents such as KK36, W9 and TPTO2 exhibited high vigor indices, suggesting a positive maternal effect. Such early-stage hybrid vigor, if maintained through to maturity, could significantly contribute to higher cashew nut yields while shortening the juvenile phase. Adu-Gyamfi et al. (2022) demonstrated that certain parents effectively transmit favorable traits, such as vigor and productivity to their offspring. These findings highlight the value of using elite genotypes as parents in future breeding programs. Selecting vigorous seedlings represents a strategic lever to enhance cashew productivity by reducing both the duration and cost of breeding cycles. While field validation under production conditions remains necessary, the results of this study support the hypothesis that early selection based on vegetative vigor can effectively guide yield-oriented genetic improvement.

Materials and methods

Experimental site

The investigation was carried out in Côte d'Ivoire in the National Agricultural Research Center (Lataha) coordinated cashew program. Lataha has geographical coordinates 9°34' North latitude and 5°34' West longitude. It is located at an altitude of 350 meters above sea level. The natural vegetation is wooded savannah with moderately denatured ferralitic soils. This geographic area is characterized by two seasons: a rainy season from May to October and a dry season from November to April. Average rainfall is 1,600 mm in a wet year and 1,100 mm in a dry year (Boko-Koiadia et al., 2016). The average temperature varies between 24°C and 33°C.

Sampling and plant material

Five genotypes KK36, W9, TPTO2, N1 and YKKF1 were used in the hybridization program. These were selected following extensive prospection and preselection missions carried out in various cashew-producing regions of Côte d'Ivoire, which led to the creation of a collection of 209 genotypes with potentially high productivity. A breeding program was then implemented to identify the most promising candidates from this collection, based on agromorphological and molecular characterization studies (Kouakou et al., 2018; Kouakou et al., 2020). The selection of these five genotypes was further supported by their consistent performance over 4 to 5 years of evaluation, based on four key criteria: average tree yield, nut production, proportion of healthy nuts (minimum 25%) and resistance to pests (Table 3). These parental lines are therefore considered strong candidates for improving cashew productivity.

Creation of hybrids by controlled pollination

Crosses were carried out using a full 5 × 5 diallel design without parents' design. Manual pollinations were conducted over two production seasons (2020/2021 and 2021/2022). Healthy panicles free from disease and pest infestation were selected for pollination (Fig. 6a). These panicles were chosen at floral developmental stages 517 and 519 as defined by Adiga et al. (2019) which correspond to swollen floral buds. Once selected, the panicles were bagged using organza bags (Fig. 6b) to isolate male and female flowers from external pollen contamination. Manual pollination was performed by gently rubbing pollen from the mature anthers of male flowers onto the receptive stigmas of female flowers (Fig. 6c). The resulting cashew nuts from these crosses constituted the seeds of the hybrid families (Fig. 6d). In total, 20 hybrid families were successfully obtained from the diallel crosses.

Assessment of cashew hybrids in the nursery and data collection

The nursery of hybrid seedlings resulting from direct and reciprocal crosses was established using a randomized complete block design (RCBD) with three replicates. The trial was conducted over a six-month period from May 2022 to November 2022. The experimental nursery covered an area of 585 m^2 (9 m × 65 m) and was divided into three blocks each spaced 2 meters apart. Each block consisted of 20 plots separated by 1 meter with each plot dedicated to a single hybrid family. Each plot contained 10 plants spaced 1 meter apart amounting to 200 plants per block. The surface area of each block was 171 m^2 (9 m × 19 m). Standard practices for cashew seedling production in nurseries were followed.

Ten morphological or vegetative traits associated with seedling vigor and known to be correlated with cashew nut yield (Aliyu, 2006; Adu-Gyamfi et al., 2020) were measured (Table 4). Data were collected from 10 sampled plants per block totaling 30 plants per hybrid family at 30, 60, 90 and 180 days of age. These time points represent critical stages for transplanting and are considered key determinants of future productivity in cashew cultivation.

Statistical Analysis of Data

Data collected at intervals of 30, 60, 90 and 180 days were analyzed using growth curves to visualize trends and growth phases of the different hybrid families. These analyses were performed using R software (version 4.2.1). To compare seedling growth at 180 days a one-way analysis of variance (ANOVA) was conducted for each vegetative trait in order to determine which traits showed significant differences among hybrids. When ANOVA results were significant ($p < 0.001$), Tukey's Honest Significant Difference (HSD) test was applied at the 5% probability level for mean separation and to rank the hybrids for each vegetative trait. Pearson correlation coefficients were calculated to assess the linear relationship between pairs of continuous vegetative traits. Additionally, Principal Component Analysis (PCA) was performed using standardized mean values for each trait to identify the main traits contributing to the observed variability in seedling growth. The PCA also enabled grouping of hybrid families in a two-dimensional space based on their similarity in vegetative traits. Finally, vigor indices (VI) were computed to classify the hybrid families into high, medium and low performance groups using the following formula:

$$VI = \sum_{i=1}^{n} w_i \cdot \left(\frac{X_i}{X_{i,max}}\right)$$

Where X_i is the value observed for the i-th parameter, $X_{i,max}$ is the maximum value observed for the i-th parameter in the data set, w_i is the weighting coefficient associated with the i-th parameter and n is the total number of parameters included in the calculation.

Conclusion

This study highlights that nursery-stage selection represents a strategic step for improving cashew productivity by enabling the early identification of the most promising genetic combinations. Early morphological traits which are correlated with the potential productivity of mature trees can effectively guide breeding programs toward the development of high-yielding and vigorous varieties. The results of this study showed that hybrid seedlings involving the parent genotypes KK36, W9 and TPTO2 were consistently associated with more vigorous growth while those involving YKKF1 tended to exhibit lower performance. The hybrids KK36×W9, KK36×TPTO2 and KK36×N1 demonstrated superior growth vigor as early as 90 days after germination. These vigorous hybrids represent valuable breeding material for improving cashew productivity. However, their performance should be validated under multi-site field conditions to assess their stability across diverse agroecological zones. Overall, this study underscores the importance of early-stage selection as a key strategy for enhancing cashew tree productivity.

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References

Adiga JD, Muralidhara BM, Preethi P, Savadi S (2019) Phenological growth stages of the cashew tree (*Anacardium occidentale* L.) according to the extended BBCH scale. Annals of Applied Biology. 175(2):246-252. https://doi.org/10.1111/aab.12526

Adu-Gyamfi PK, Akpertey A, Barnnor M, Ofori A, Padi F (2020) Genotypic characterization of cashew (*Anacardium occidentale* L.) clones using agro-morphological traits. Plant-Environment Interactions. 1(3):196-206. https://doi.org/10.1002/pei3.10034

Adu-Gyamfi PK, Barnnor M, Akpertey A, Padi, F (2022) Genetic variability and combining abilities for earliness to nut yield and nut weight in selected cashew (*Anacardium occidentale* L.) clones. International Journal of Fruit Science. 22(1):539-550. https://doi.org/10.1080/15538362.2022.2070575

Akpertey A, Dadzie AM, Adu-Gyamfi PKK, Ofori A, Padi FK (2017) Effectiveness of juvenile traits as selection criteria for yield efficiency in kola. Scientia Horticulturae. 216:264-271. https://doi.org/10.1016/j.scienta.2017.01.018

Aliyu OM (2006) Phenotypic correlation and path coefficient analysis of nut yield and yield components in cashew (*Anacardium occidentale* L.). Silvae Genetica. 55(1):19-24. https://doi.org/10.1515/sg-2006-0004

Aliyu OM, Awopetu JA (2007) Assessment of genetic diversity in three populations of cashew (*Anacardium occidentale* L) using protein-isoenzyme-electrophoretic analysis. Genetic Resources and Crop Evolution. 54:1489-1497. https://doi.org/10.1007/s10722-006-9138-9

Atay E, Koyuncu F (2022). The effects of branching-promoter treatments on nursery tree quality in Braeburn and Granny Smith apple cultivars. Anadolu Ege Tarımsal Araştırma Enstitüsü Dergisi, 32: 86-101.

Boko-Koiadia AN, Cissé G, Koné B, Séri D (2016) Variabilité climatique et changements dans l'environnement à Korhogo en Côte d'Ivoire : mythes ou réalité ? European Scientific Journal. 12(5):158-176. https://doi.org/1019044/esj2016v12n5p158

Chen YY, Li NY, Guo X, Huang HJ, Garcia-Oliveira P, Sun JY, Liu C (2023) The nutritional and bio-active constituents, functional activities, and industrial applications of cashew (*Anacardium occidentale* L.): A Review Food Frontiers. 4(4):1606-1621. https://doi.org/101002/fft2250

Dadzie AM, Adu-Gyamfi PKK, Opoku SY, Yeboah J, Akpertey A, Opoku-Ameyaw K, Danquah WB (2014) Evaluation of potential cashew clones for utilization in Ghana. Advances in Biological Chemistry. 4: 232-239. https://doi.org/104236/abc201444028

Dedehou ES, Dossou J, Soumanou MM (2015) Etude diagnostique des technologies de transformation de la pomme de cajou en jus au Bénin. International Journal of Biological and Chemical Sciences. 9 (1):371-387. https://doi.org/104314/ijbcsv9i132

Dendena B, Corsi S (2014) Cashew, from seed to market: A review. Agronomy for Sustainable Development. 34(4):753–772. https://doi.org/101007/s13593-014-0240-7

Eradasappa E, Adiga, JD, Mohana G (2020) Hybrid vigour and variability for key growth characters and yield in cashew (*Anacardium occidentale* L.). Journal of Plantation Crops. 48(2):71-81. https://doi.org/1025081/jpc2020v48i26365

FIRCA (2018) La filière du progrès, Bulletins d'information n20 du Fonds Interprofessionnel pour la Recherche et le Conseils Agricoles, pp 51. https://fircaci/ressources/publications/bulletins-dinformation/. Accessed 26 October 2024

FIRCA (2022) La filière du progrès, Rapport annuel 2022 du Fonds Interprofessionnel pour la Recherche et le Conseil Agricoles, pp 85-93. https://fircaci/ressources/publications/rapports-annuels-et-bilans/. Accessed 26 October 2024

Franco JA, Martínez-Sánchez JJ, Fernández JA, Bañón S (2006) Selection and nursery production of ornamental plants for landscaping and xerogardening in semi-arid environments. The Journal of Horticultural Science and Biotechnology. 81(1): 3-17. https://doi.org/10.1080/14620316.2006.11512022

Gonçalves PS & Marques JRB (2014) Clones de Seringueira: Influência dos Fatores ambientais na Produção e recomendação para o plantio. In: Alvarenga AP (Eds.) Seringueira. Viçosa, Epamig. p.247-325.

Grossnickle SC, MacDonald JE (2018) Why seedlings grow: influence of plant attributes. New forests. 49:1-34. https://doi.org/10.1007/s11056-017-9606-4

Ingram V, Yago-Ouattara EL, Lartey A, Mogre D, Wijnands J, Van Den Berg J (2015) Gender dynamics in cashew and shea value chains from Ghana and Burkina Faso. Report/LEI Wageningen UR

Kouakou CK, Konan ADSH, N'Da Adopo AA, N'Da HA, Djaha AJB, Minhibo MY, N'Guessan AEB (2018) Agro-morphological characterization of cashew (*Anacardium occidentale* L.) ecotypes from North-Central of Côte d'Ivoire. Fruits. 73(5):255-264. https://doi.org/1017660/th2018/7351

Kouakou CK, N'Da Adopo AA, Djaha AJB, N'Da HA, Bi IAZ, N'Guessan AE (2020) Genetic characterization of promising high-yielding cashew (*Anacardium occidentale* L.) cultivars from Côte d'Ivoire. Biotechnology, Agronomy Society and Environment. 24:46–58. https://doi.org/1025518/1780-450718464

Mackay IJ, Cockram J, Howell P, Powell W (2021) Understanding the classics: the unifying concepts of transgressive segregation, inbreeding depression and heterosis and their central relevance for crop breeding. Plant Biotechnology Journal. 19(1): 26-34. https://doi.org/101111/pbi13481

Masawe PAL (2006) Tanzanian Cashew Cultivars Selected Clones Cashew Research Programme, Naliendele Agricultural Research Institute, Mtwara, Tanzania

Masawe PAL, Kapinga FA, Madeni JP, Majune D, Ngamba, ZS (2017) Performance of 26 selected elite cashew hybrids under the conditions of Nachingwea in Southern Tanzania Short title Performance of 26 selected elite cashew hybrids in Southern Tanzania. Colloque International d'Échanges Scientifiques sur l'Anacarde Presses Agronomiques de Gembloux, Grand Bassam (Côte d'Ivoire), pp 15–20. Available at : ISBN 978-2-87016-166-1

Masawe PAL, Kapinga, FA (2016) The first African elite cashew hybrids New cashew varieties in Tanzania Cashew Research Programme, Tanzania Agricultural Research Institute. Available at: ISBN: 978-9987-446-10-0

Mog B, Janani P, Nayak MG, Adiga JD Meena R (2019) Manipulation of vegetative growth and improvement of yield potential of cashew (*Anacardium occidentale* L.) by Paclobutrazol. Scientia Horticulturae. 257, 108748. https://doi.org/10.1016/j.scienta.2019.108748

Mog B, Nayak MG (2018) Leaf morphological and physiological traits and their significance in yield improvement of fifteen cashew varieties in West Coast Region of Karnataka. International Journal of Current Microbiology and Applied Science. 7: 1455-1469. https://doi.org/10.20546/ijcmas.2018.707.173

Monteiro F, Catarino L, Batista D, Indjai B, Cristina Duarte M, Romeiras MM (2017) Cashew as a high agricultural commodity in West Africa: Insights towards sustainable production in Guinea-Bissau. Sustainability. 9 (9):1666. https://doi.org/103390/su9091666

Nyirenda J, Zombe K, Kalaba G, Siabbamba C, Mukela I (2021) Exhaustive valorization of cashew nut shell waste as a potential bioresource material. Scientific Reports. 11(1):11986. https://doi.org/101038/s41598-021-91571-y

Pâques LE (2009) Growth rhythm parameters as components of hybrid vigour in young seedlings of hybrid larch (*Larix decidua* x *L. kaempferi*). Silvae Genetica. 58(1-2): 42-53. https://doi.org/10.1515/sg-2009-0006

Rege A, Lee JSH (2022) State-led agricultural subsidies drive monoculture cultivar cashew expansion in northern Western Ghats, India. PloS one. 7(6): e0269092. https://doi.org/101371/journalpone0269092

Roy A, Fajardie P, Lepoittevin B, Baudoux J, Lapinte V, Caillol S, Briou B (2022) CNSL, a promising building blocks for sustainable molecular design of surfactants: a critical review. Molecules. 27(4): 1443. https://doi.org/103390/molecules27041443

Salam MA, Peter K (2010) Cashew-a monograph, pp 257. Available at: ISBN: 978-93-80012-08-7

Savadi S, Muralidhara BM, Preethi P (2020) Advances in genomics of cashew tree: molecular tools and strategies for accelerated breeding. Tree Genetics & Genomes. 16(5): 61. https://doi.org/101007/s11295-020-01453-z

Sethi K, Lenka PC, Tripathy SK, Tripathy P (2016) Evaluation of promising cashew hybrids for higher nut yield. Journal of Plantation Crops. 44(1): 50-56. https://doiorg/1019071/jpc2016v44i13015

Syed NH, Sureshsundar S, Wilkinson MJ, Bhau BS, Cavalcanti JJV, Flavell AJ (2005) Ty1-copia retrotransposon-based SSAP marker development in cashew (*Anacardium occidentale* L.). Theoretical and Applied Genetics. 110: 1195-1202. https://doi.org/101007/s00122-005-1948-1

Teixeira AL, Gonçalves FMA, Rezende JCD, Carvalho SPD, Pereira AA, Moraes BFXD Teixeira LGV (2012). Early selection for grain yield in Arabica coffee using morphological traits evaluation. Pesquisa Agropecuária Brasileira. 47:1110-1117.

Wu S, Lu Z, Xu J, Chen G, Zhu Y, Li G (2015) Genetic variation in growth traits and stem–branch characteristics and their relationships to Eucalyptus clones. Journal of Forestry Research. 26: 957-962. https://doi.org/10.1007/s11676-015-0092-2