Genetic Variability and Combining Abilities for Earliness to Nut Yield and Nut Weight in Selected Cashew (*Anacardium Occidentale* L.) Clones

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**ABSTRACT**

Introduction of exotic clones into the pedigree of commercial cashew clones could constitute a viable strategy to overcome the current low early nut yield and nut weight of the crop in West Africa. The aim of this study was to assess the combining abilities of Beninese, Brazilian and Ghanaian clones for early nut yield and nut weight. Twelve *F*$_1$ hybrids were evaluated in the field for five traits such as stem diameter increment, canopy spread, nut yield, nut weight and cropping efficiency. Significant difference (*p* ≤ .01) was observed for most of the traits. Nut weight varied from 5.3 to 10.1 g/ha/year, whilst nut yield ranged from 666.1 to 872.8 kg/ha/year among the top five crosses in the third to fifth year after planting. The Beninese (BE) progenies were comparable to the Ghanaian (SG) progenies for early nut yield but inferior to the Ghanaian and Brazilian (A) progenies for nut weight. Pearson correlation coefficient estimate (*r* = 0.74; *p* ≤ .01) suggest that, selecting for canopy spread in the north-south direction might improve early nut yield. GCA effects were more important than SCA effects. Narrow-sense heritability was moderate and exceeded 50% for all the traits. BE203 and SG224 showed positive GCA for early nut yield, whereas A2 and SG273 showed positive GCA for nut weight. Our study suggest that the Brazilian, Beninese and Ghanaian clones had different merits as potential parents for early nut yield and nut weight and could constitute a suitable genetic resource for improving cashew productivity.

**KEYWORDS**

Cashew; combining ability; complementary traits; earliness; germplasm

**Introduction**

Cashew (*Anacardium occidentale* L.) is a perennial nut tree crop belonging to one of the most important genera of the family Anacardiaceae. It is native to north-eastern Brazil but was introduced to West Africa by the early Portuguese settlers in the 16th century (Mitchell and Mori, 1987; Salam and Peter, 2010). Currently, about 45% of the world’s cashew production comes from West Africa, with Ivory Coast, Ghana and Nigeria being major producers (Monteiro et al., 2017).

Cashew is highly valued for its nuts, which are processed into products like roasted kernel snacks, kernel oil, cashew nut shell liquid and their apples that are developed into juice, jam and alcohol. The apples are known to be rich in vitamin C, whereas the kernels contain unsaturated fatty acids low in cholesterol (Grundy, 1987). The crop has been a major foreign exchange earner for many developing countries in the tropical and subtropical regions of the world (Oliveira, 2008). Its potential in alleviating poverty and boosting rural development has been highlighted (Dendena and Corsi, 2014; Ingram et al., 2015; Wongnaa and Awunyo-Vitor, 2013).
However, recently, cashew productivity has been constrained by low nut yield and poor nut quality (Adu-Gyamfi et al. 2019; Dadzie et al., 2014; Rabany et al., 2015). The situation is made worse by the narrow genetic base of recommended cashew varieties and the change in production environment (long dry spells, erratic rainfall patterns and extreme temperature). In Ghana, recommended cashew clones for farmers have given low early nut yields in the range of 210.4–625 kg ha\(^{-1}\) with low nut weights from 5.2 to 6.3 g at 5 years after planting in the Forest transitional agroecological zone, which holds the largest concentration of commercial cashew farms (Adu-Gyamfi et al. 2019). Meanwhile, Masawe et al. (1999) reported relatively higher nut yields in the range of 1,700–2,400 kg ha\(^{-1}\), with a mean nut weight of 8.3 g from a hybrid variety (AC4 × AZA17) at 6 years after planting.

Over the years, a number of genetically diverse cashew germplasm accessions have been introduced from the center of origin to various cashew-growing countries. In Ghana, the first formal cashew germplasm introductions occurred between the years of 2004–2006 under the Cashew Development Project, which was funded by the African development Bank (AfDB). These introductions consisted mainly of accessions and clones from Brazil, Benin, Nigeria, Mozambique and Tanzania and breeding programs have primarily focused on the characterization, evaluation and utilization of these introductions (Dadzie et al., 2014). Currently, recommended cashew clones for farmers comes from local germplasm collections made in the mid 90s (Personal communication – Seth Osei- Akoto). These clones have produced relatively low early nut yields with smaller nut weights across the cashew production belt (Adu-Gyamfi et al. 2019; Dadzie et al., 2014). The situation is made worse by the recent awareness that, nut weight is the major criterion that determines the market value of nuts and kernels in the cashew global trade. Farmers and cashew processors are therefore demanding cashew varieties that provide early nut yields with extra large nuts that could offer high profitability in the cashew farming business through the premium price offered from buyers.

Recently, efforts to improve cashew productivity have strongly emphasized the introgression of desirable alleles from exotic germplasm (Cavalcanti et al., 2007a; Padi et al., 2017). The dwarf cashew population introduced from Brazil are known to be precocious and a repository of genes of larger nuts sizes “bolder nuts” with larger kernel weights (Aliyu and Adedokun Awopetu, 2011) whilst those from Benin were precocious and may possess alleles with high water and nutrient use efficiency (Adu-Gyamfi et al. 2019). The occurrence of the Ghanaian cashew clones, which are locally adapted and the Brazilian clones producing high premium kernels (W180 – W240) and the Benin clones with high water and nutrient efficiency indicate a good opportunity for early nut yield and nut quality improvement.

However, knowledge of their combining abilities for vigor, nut yield, nut weight and cropping efficiency (relates to a significant reduction in vegetative vigor and size during production, minimizing any adverse effect of high seedling vigor on crop management) are important for the current cashew breeding program that focuses on progenies as varieties. A number of combining ability studies have been conducted on cashew. Cavalcanti et al. (1997) observed significant effect of both GCA and SCA on early nut yield in Brazilian Dwarf cashew. Sankaranarayanan et al. (2011) also reported the preponderance of non-additive effects for vigor in cashew seedlings. In addition, the phenotypic performance of morphological traits, such as plant height, canopy diameter, kernel weight and nut weight in cashew were found to be governed by additive effects (Cavalcanti et al., 2007a).

Tree canopy characteristics has implications on yield and quality (Wen et al., 2020). This has been attributed to the different microclimates that are presented across the sides of the tree canopy due to environmental factors such as light, temperature and humidity (Matloobi, 2012). Light distribution within the canopy has been found to affect the photosynthetic capacity of the leaves (Jones, 1984; Matloobi, 2012). Wen et al. (2020) reported significant positive correlations between light intensity, temperature and yield in the canopies of chestnut trees. Similarly, in cashew, Sethi et al. (2016) highlighted that wider canopy spread in the north-south direction is a preferred trait as it receives enough sunshine to produce higher nut yields compared to the east-west direction.
As many of the tree crops, cashew long life cycle in addition to large resources and labor are required for effective evaluation. To reduce the labor and time involved, juvenile traits such as vigor and early nut yield traits have been used as indices for selecting high yielding genotypes in later years (Glendinning, 1960; Padi et al., 2012). In using early juvenile traits to select potential parental clones, knowledge of the relationship between traits and parental values in crosses are crucial. This ensures that efficient parental choices are made and genetic breeding progress are predicted in breeding programs, especially when parents are selected base on the progeny performance.

The objective of the present study was to (i) determine the combining abilities of Brazilian, Beninese and Ghanaian cashew clones for vigor, early nut yield and nut weight (ii) estimate the heritability and correlations between vigor and early nut yield traits. Such a project with the mentioned clones has not been carried out previously.

**Materials and methods**

**Plant Material**

The plant material used in this experiment consisted of three female, SG266, SG276 and SG287 and four male A2, BE203, SG273 and SG224 clones to generate F1 progenies. These parental clones were chosen based on complementary yield traits. The female clones were recommended and well adapted to local conditions. The two male exotic clones include the Beninese clone BE203 selected for early nut yield (Adu-Gyamfi et al. 2019) and the Brazilian dwarf clone A2 selected for early nut yield and large nut weight (the average number of nuts produced in 1 kg of raw cashew nuts)(Aliyu and Adedokun Awopetu, 2011). Manual pollinations were done during October 2011 – February 2012 to produce 12 combinations of F1 following a North Carolina II (NC II) mating scheme. A description of the characteristics of parental clones utilized is given in Table 1.

**Field Evaluation**

The experiment was conducted at the Wenchi Agricultural Research Station (N 07° 45, 740°, W 002° 05, 440°), which is situated in the Forest Transitional Agro-ecological zone of Ghana. This zone is characterized by a mean annual rainfall of 1300 mm and average annual temperature range of 26.1–28.9 °C (Lacombe et al., 2012; Owusu and Waylen, 2013). The soils in this zone are predominantly lithosols, with organic matter content in the range of 0.34–1.7% and pH range of 4.1–7.7 (Dedzoe et al., 2001). The available phosphorus and calcium in the soil also range from 0.12–64.30 mg/kg and 16.00–140.30 mg/kg, respectively (MOFA, 2018). The trial was laid out in a randomized complete block design with three replications of 12 plants per plot at a spacing of 10 m × 10 m (100 plants per hectare) in June, 2012. The standard practices for cashew production in Ghana were duly followed. This experiment constitute the first formal cashew hybridization program in Ghana.

Table 1. Description of characteristics of the cashew clones used as parents for the progenies in a 3 × 4 factorial mating design.

| Parent | Source of germplasm | Characteristics |
|--------|---------------------|-----------------|
| A2     | Brazil              | Dwarf cashew, large nut size (8–12 g), precocious. |
| BE203  | Benin               | Common cashew, medium nut size (7–9 g), High nut yield (669.2 kg ha⁻¹), precocious, high water and nutrient use efficient, high outturn (31%). |
| SG224  | Ghana (local)       | Common cashew, smaller nut size (6.1 g), moderate nut yield (625.8 kg ha⁻¹) (Adu-Gyamfi et al 2019). |
| SG273  | Ghana (local)       | Common cashew, smaller nut size (5.3 g), moderate nut yield (368.3 kg ha⁻¹) (Adu-Gyamfi et al 2019). |
| SG266  | Ghana (local)       | Common cashew, smaller nut size (5.8 g), moderate nut yield (561.4 kg ha⁻¹) (Adu-Gyamfi et al 2019). |
| SG276  | Ghana (local)       | Common cashew, smaller nut size (6.3 g), moderate nut yield (400 kg ha⁻¹) (Adu-Gyamfi et al 2019). |
| SG287  | Ghana (local)       | Common cashew, smaller nut size (5–6.9 g), moderate nut yield (422 kg ha⁻¹) (Adu-Gyamfi et al 2019). |
Data Collection

The stem diameter of young cashew plants (vigor) was measured at 15 cm from the soil surface with electronic callipers at six-month intervals from December 2012 to December 2014 and from December 2015 to December 2017 for the juvenile and reproductive periods, respectively. Data on yield per plot per annum was estimated from the weight of nuts collected from each clone throughout the fruiting season between 2015 and 2017 cropping years. Nut weight (g) was estimated as the weight of 1 kg of raw cashew nuts divided by the number of nuts. Plant height was recorded by measuring from the base of the plant (soil surface) to the apex of the plant. Canopy spread was measured by marking each tree on the side as north, south, east and west with the help of a GPS device. Measurements were taken from east to west (EW) and north to south (NS) direction at yearly intervals using a tape measure during 2014–2016. Earliness to nut yield was measured as the average annual nut yield obtained in the fourth and fifth years of production during October 2015 – April 2017.

Data Analysis

For the agronomic data obtained, plot-level values were used in the analysis of variance (ANOVA) following tests for normality (based on the plot of residuals). All 12 F1 progenies were analyzed to test for significant differences among the varieties using the cumulative or average trait values across years, with hybrid families considered as fixed factor and replicates as random factor, using the GenStat statistical software, version 12 (VSN International Ltd., Hemel Hempstead, UK). The general and specific combining ability (GCA and SCA) effect, narrow-sense heritability, additive variance, dominance variance and genotypic variance were estimated using AGD-R (Analysis for Genetic Designs) with R windows software (Rodriguez et al. 2018). The GCA and SCA effects were estimated with the following model.

\[ Y_{ijk} = \mu + r_k + m_i + f_j + m_i * f_j + e_{ijk}. \]

where \( Y_{ijk} \) is the observed value; \( \mu \) is the population mean effect; \( r_k \) is the replicate effect (\( k = 1, 2, \ldots, r \)); \( m_i \) is the male GCA effect (\( i = 1, 2, \ldots, m \)); \( f_j \) is the female GCA effect (\( j = 1, 2, \ldots, f \)); \( m_i * f_j \) is the SCA effect and \( e_{ijk} \) is the residual effect. The phenotypic correlations between two traits, i and j, were estimated using META – R statistical package (Alvarado et al. 2018). The analysis on growth (stem-diameter increment and plant-height increments) utilized the difference between the initial and final stem diameter/plant height measurements taken from December 2012 to December 2014. The GCA and SCA ratios for each trait was determined following the general predicted ratio (GPR) for both male and female parents: GCA/SCA = 2 MSGCA/(2 MSGCA + MSSCA) according to (Baker, 1978).

Results

Performance of F1 Progenies for Vigor, Nut Yield Related Traits

Among the 12 F1 progenies evaluated, significant differences (\( P < .05 \)) were observed for most traits (Table 2). In terms of vigor, which was expressed as stem diameter increment at the vegetative stage, the performance of the Beninese and the Ghanaian progenies (with SG224 as male parent) were comparable but superior to Brazilian progenies with a vigor advantage of 11% (11.2 cm). The Beninese progeny SG266 × BE203 was the most vigorous with stem diameter of 107.9 cm whereas the Brazilian progeny SG266 × A2 was the least vigorous with stem diameter of 79.5 cm (Table 3).

Similarly, for early nut yields, the Ghanaian progenies (with SG224 as male parent) were comparable to the Beninese progenies, but demonstrated a nut yield advantage of 24% (166 kg ha\(^{-1}\)) over the Brazilian progenies. However, regarding nut weights, the Ghanaian progenies (with SG273 as male parent) were superior (6.0–10.1 g) to the Brazilian (5.9–8.6 g) and Beninese progenies (6.0–7.4 g), respectively (Table 3). Progenies SG287 × BE203, SG287 × SG273 and SG276 × SG224 were the best three highest nut yielding (738.3–872.8 kg ha\(^{-1}\)) varieties with nut weights of 7.4 g, 7.2 g and 7.3 g, respectively. On the other hand, SG266 × SG273, SG266 × A2 and SG276 × A2 were the three lowest
nut yielding (448–563 kg ha\(^{-1}\)) progenies but with relatively larger nut weights of 10.1 g, 8.6 g, and 8.1 g respectively. Comparatively, the performance of the Ghanaian and the Beninese progenies appeared to be equivalent in terms of vigor and early nut yield whilst the Brazilian progenies appeared to be intermediate for nut weight performance.

**Analysis of Variance**

The male GCA effects were significant (\(p \leq .05\)) for all the traits except stem diameter increment in the reproductive period; however, the female GCA effects were only significant (\(p \leq .001\)) for stem diameter during the reproductive period (Table 2). SCA effects were also significant for all the traits, with the exception of height and canopy spread in the east-west (EW) direction. The male GCA/SCA ratio for SDI (vegetative), nut yield and nut weight were > 0.50 whilst the female was < 0.50. This indicate that these traits are determined by both additive and non – additive genetic effects originating from the maternal and paternal parents (Table 2). On the other side, GCA/SCA ratios for both male and female parents were > 0.50 for height, canopy spread in the NS and EW directions, SDI in the reproductive stage and cropping efficiency. This implied that these traits were determined by mainly additive genetic effects. However, the ratio of the additive (GCA) to dominance (SCA) variance was much higher than unity for most of the traits which indicates the predominance of GCA effects in controlling most of the traits. For all the traits, the additive variance component was much larger than that due to the dominance variance component from the pooled variance of female and male effects (Table 4). Comparatively, variability among the female parents (variance component due to female parents) was low (< 0.1) for all the traits (except SDI at the reproductive stage) whereas among the male parents (variance component due to male parent), variability was moderate (> 0.1) for all the traits except for SDI at the reproductive stage (Table 4). Narrow-sense heritability estimates were moderate and exceeded 50% for all the traits in this study.

**Correlation Among Traits**

The phenotypic correlation estimates among traits demonstrated that nut yield was strongly correlated with cropping efficiency (\(r = 0.92, p < .001\)) and correlated with height (\(r = 0.68, p < .01\)), canopy spread-NS (\(r = 0.74, p < .01\)) and canopy spread-EW (\(r = 0.65, p < .05\)) (Table 5). Stem diameter increment during the vegetative period was moderately correlated with canopy spread-NS (\(r = 0.60, p < .05\)) and height (\(r = 0.61, p < .05\)). Cropping efficiency was positively correlated with canopy spread – NS (\(r = 0.64, p < .05\)).

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**Table 2.** Means squares from analysis of variance and significance test of 12 cashew progenies for height, stem diameter increment, canopy spread, nut yield, nut size and cropping efficiency at Wenchi from 2012 to 2017.

| Source of Variation | Df | Height (Vegetative) (cm) | Canopy Spread (NS) (m) | Canopy Spread (EW) (m) | SDI (Reproductive) (cm) | Nut yield (kg ha\(^{-1}\)) | Cropping efficiency (g/cm\(^2\)/yr) | Nut weight (g) |
|---------------------|----|-------------------------|------------------------|------------------------|-------------------------|--------------------------|--------------------------------|----------------|
| Replication         | 2  | 0.381                   | 308.93*                | 0.161                  | 0.237*                  | 6243                     | 73591*                         | 1436.7*        |
| GCA Male            | 3  | 0.133*                  | 188.29**               | 1.127*                 | 1.144*                  | 8345                     | 57479**                         | 1198*          |
| GCA Female          | 2  | 0.12                    | 18.66                  | 0.4842                 | 0.44                    | 26270***                 | 11710                          | 1185.4         |
| SCA (Male x Female) | 6  | 0.035                   | 138.69**               | 0.8565*                | 0.3065                  | 6511*                    | 39392**                         | 863.6*         |
| Error               | 14 | 0.04                    | 41.06                  | 0.3858                 | 0.5628                  | 2615                     | 16833                          | 426.5          |
| GCA/SCA male        | 0.88 | 0.73                  | 0.72                   | 0.88                   | 0.72                    | 0.74                      | 0.74                           | 0.69           |
| GCA/SCA female      | 0.87 | 0.21                  | 0.53                   | 0.74                   | 0.89                    | 0.37                      | 0.73                           | 0.17           |

\* \* \*** significantly different at \(p \leq 0.05\ p \leq 0.01\) and \(p \leq 0.001\); SDI – Stem diameter increment, NS – North-South, EW – East-West.

\* GCA/SCA \_ male = Ratio of GCA and SCA for male parents, GCA/SCA \_ female = ratio of GCA and SCA for female parents.
Table 3. Estimates of GCA effects and the mean growth and yield performance of 12 cashew progenies derived from a factorial mating design of three females and four males and evaluated at Wenchi from 2012 to 2017.

| Parent    | SDI (vegetative) (cm) | Height (m) | Canopy spread (EW) (m) | Canopy spread (NS) (m) | SDI (reproductive) (cm) | Nut yield (kg ha⁻¹) | Cropping efficiency (g/cm²/yr) | Nut weight (g) |
|-----------|-----------------------|------------|------------------------|------------------------|-------------------------|---------------------|-------------------------------|---------------|
| **Males** |                       |            |                        |                        |                         |                     |                               |               |
| A2        | –2.544*               | –0.121*    | –0.199                 | –0.166                 | 0.001                   | –20.278*           | –0.125*                      | 0.318*        |
| BE203     | 1.757                 | –0.004     | 0.342*                 | –0.026                 | 0.003                   | 15.294*            | 0.121*                       | –0.15         |
| SG224     | 0.699                 | 0.040      | –0.021                 | 0.221*                 | –0.002                  | 7.683*             | 0.033                        | –0.545*       |
| SG273     | 0.089                 | 0.086      | –0.122                 | –0.029                 | –0.003                  | –2.698             | –0.029                       | 0.377*        |
| SE0.05    | 1.101                 | 0.055      | 0.151                  | 0.08                   | 0.010                   | 3.94                | 0.012                        | 0.15          |
| **Females** |               |            |                        |                        |                         |                     |                               |               |
| SG266     | 0.001                 | –0.003     | 0.002                  | 0.004                  | 31.712*                 | 0.001              | 0.001                        | 0.003         |
| SG276     | –0.001                | 0.001      | 0.002                  | 0.003                  | 6.82                    | 0.003              | 0.002                        | 0.001         |
| SG287     | –0.004                | –0.001     | 0.004                  | –38.32*                | –0.004                  | –0.001             | –0.001                      | –0.001        |
| SE 0.05   | 0.121                 | 0.024      | 0.021                  | 0.014                  | 7.05                    | 0.021              | 0.011                        | 0.021         |
| **Progeny** |               |            |                        |                        |                         |                     |                               |               |
| SG287 × BE203 | 94.9              | 2.2        | 4.2                    | 3.5                    | 666.1                   | 872.8              | 130.9                        | 7.4           |
| SG266 × SG24 | 96.2              | 2.3        | 3.6                    | 3.8                    | 702.8                   | 789.4              | 113.6                        | 5.3           |
| SG287 × SG273 | 93.3              | 2.2        | 3.3                    | 3.6                    | 637.3                   | 743.9              | 116.8                        | 7.2           |
| SG276 × SG24 | 92.8              | 2.4        | 3.7                    | 3.7                    | 670                     | 738.3              | 109.9                        | 7.3           |
| SG276 × SG273 | 98.1              | 2.3        | 3.9                    | 3.1                    | 774.3                   | 666.1              | 88.9                         | 6             |
| SG266 × BE203 | 107.9             | 2.3        | 3.8                    | 3.3                    | 837.5                   | 610.6              | 73.4                         | 6             |
| SG276 × BE203 | 87.6              | 2.1        | 3.9                    | 1.9                    | 647.5                   | 594.7              | 93.5                         | 6.1           |
| SG287 × SG24 | 94.6              | 2.1        | 3.3                    | 3.3                    | 624.1                   | 577.8              | 93.3                         | 5.4           |
| SG266 × A2   | 79.5              | 2.1        | 3.6                    | 2.4                    | 715.6                   | 563                | 78.9                         | 8.6           |
| SG276 × A2   | 92.2              | 2.3        | 3.6                    | 2.6                    | 710.5                   | 528.3              | 74.7                         | 8.1           |
| SG287 × A2   | 85.2              | 1.9        | 3.4                    | 2.9                    | 645.5                   | 490                | 76.8                         | 5.9           |
| SG266 × SG273 | 85.3              | 2.1        | 2.9                    | 2.1                    | 612.1                   | 448                | 75.4                         | 10.1          |
| **Mean**    | 92.3              | 2.1        | 3.6                    | 3.0                    | 686.9                   | 635.2              | 93.8                         | 6.9           |
| **SED**     | 5.2               | 0.21       | 0.77                   | 0.61                   | 42.95                   | 106.1              | 16.8                         | 0.49          |

* SDI – Stem diameter increment, NS – North-South, EW – East-West. **, *** significantly different at p ≤ 0.05 and p ≤ 0.01
Table 4. Variance components from the performance of 12 cashew progenies derived from a factorial mating of three females and four males and evaluated at Wenchi from 2012 to 2017.

| Variance components | Height (m) | SDI (mm) (vegetative) | SDI (mm) (reproductive) | Canopy spread (NS) | Canopy spread (EW) | Nut weight (g) | Nut Yield (kg ha\(^{-1}\)) | Cropping efficiency (g/cm\(^2\)/year) |
|---------------------|------------|------------------------|-------------------------|---------------------|---------------------|----------------|-----------------------------|-----------------------------------|
| \(\sigma^2_m\)    | 0.014      | 9.18                   | 0                       | 0.07                | 0.099               | 0.43           | 1529.85                     | 0.15                              |
| \(\sigma^2_f\)    | 0          | 0                      | 1851.64                 | 0                   | 0                   | 0              | 0                           | 0                                 |
| \(\sigma^2 (m \times f)\) | 0.015      | 29.33                  | 1873.59                 | 0.12                | 0.001               | 1.45           | 17438.69                    | 3.34                              |
| \(\sigma^2 A\)    | 0.101      | 150.1                  | 13451.69                | 0.76                | 0.215               | 7.25           | 74953.53                    | 13.85                             |
| \(\sigma^2 D\)    | 0.058      | 117.3                  | 7494.34                 | 0.47                | 0.11                | 5.8            | 69754.75                    | 13.38                             |
| \(\sigma^2 A \times D\) | 1.7        | 1.3                    | 1.8                     | 1.6                 | 1.9                 | 1.3            | 1.1                        | 1.0                               |
| \(h^2 n\)         | 0.59 ± 0.04| 0.55 ± 0.02            | 0.62 ± 0.01            | 0.55 ± 0.02         | 0.57 ± 0.03         | 0.53 ± 0.07     | 0.51 ± 0.03                 | 0.51 ± 0.07                        |

a SDI- Stem diameter Increment, NS – North-South, EW – East-West.
b \(\sigma^2\) (m) is the variance component due to males, \(\sigma^2\) (f) is the variance component due to females, \(\sigma^2\) (A) is the additive variance component, \(\sigma^2\) (D) is the dominance variance component, and \(\sigma^2\) (A) \(\times\) \(\sigma^2\) (D) is the additive: dominance variance ratio, \(h^2\) (n) is the narrow sense heritability.
Table 5. Pearson’s phenotypic correlation coefficients and significance test for survival, stem diameter increment, height, canopy spread, nut yield, cropping efficiency and nut weight among 12 cashew progenies evaluated at Wenchi from 2012 to 2017.

| Trait                      | Nut yield (kg ha⁻¹) | Canopy spread (EW) | Canopy spread (NS) | Height (m) | Nut weight (g) | SDI reproductive (cm) | SDI Vegetative (cm) |
|----------------------------|---------------------|--------------------|--------------------|------------|----------------|------------------------|---------------------|
| Canopy spread -EW (m)      | 0.65*               | 0.27               | 0.59*              |            |                |                        |                     |
| Canopy spread -NS (m)      | 0.74**              | 0.49               |                    |            |                |                        |                     |
| Height (m)                 | 0.68**              | 0.49               | 0.59*              | -0.31      | -0.50          | -0.19                  | -0.25               |
| Nut weight (g)             | -0.31               | -0.44              | -0.50             | -0.19      |                |                        |                     |
| SDI reproductive (mm)      | 0.11                | 0.40               | 0.61*              | 0.43       | 0.61*          | 0.06*                  | 0.19                |
| SDI vegetative (mm)        | 0.44                | 0.34               | 0.60*              | 0.61*      | 0.62*          | 0.06*                  |                     |
| Cropping efficiency (g/cm/year) | 0.92***          | 0.47               | 0.64*              | 0.49       | -0.21          | -0.29                  | 0.19                |

* Significant at p ≤ 0.05. ** Significant at p ≤ 0.01. *** Significant at p ≤ 0.001. SDI – Stem diameter increment.

General Combining Abilities

Significant (p ≤ .05) male GCA were observed for all the traits and highly significant (p < .001) female GCA was observed for only SDI at reproductive stage (Table 3). During the vegetative period (2012–2014), the Brazilian clone A2 contributed negatively, toward GCA effect for vigor (height and stem diameter increment). However at the reproductive period, the female parent SG266 contributed positively toward GCA effect for stem diameter increment, whilst SG278 contributed negatively (Table 3). On the other hand, the Brazilian clone A2 together with the Ghanaian clone SG273 contributed positively toward GCA effects for nut weight whilst the Ghanaian clone SG224 contributed negatively (Table 3). For early nut yield, the Beninese clone BE203 and the Ghanaian clone SG224 contributed positively toward GCA effects, whereas the Brazilian clone A2 contributed negatively. For cropping efficiency, BE203 had a positive GCA effect and A2 affects the trait negatively.

Discussion

Although cashew commercial production in Sub-Saharan Africa has been underway for four decades, low nut yield and poor nut quality continue to limit productivity. This has been attributed to the narrow genetic base of cultivated cashew varieties (Archak et al., 2003).

In the present study, the high nut yields with large nut weights and the substantial genetic variation observed among the F1 progenies emphasize the importance of expanding the genetic base of the cashew under production for higher productivity. The considerable performance of the Ghanaian, Beninese and Brazilian progenies for vigor, early nut yield, cropping efficiency and nut weight suggest that, the variability among cashew progenies could be influenced by the origin of the parental genotypes, which offers an avenue for breeding and selection. These results were found to be consistent with the findings of previous studies (Cox, 1991; Vello et al., 1984). The significant GCA and SCA effects for some of the traits in the current study implied that both additive and non-additive gene effects were important in controlling these traits as stated by Griffing (1956). However, the much greater than unity ratio of GCA:SCA variance suggested the predominant role of additive gene effects in determining the inheritance of most of the traits. These results are consistent with other reports in cashew (Cavalcanti et al., 2000, 2007a; Wijit et al., 1992) and other tree crops like cocoa (Theobroma cacao L.) (Pang, 2006; Tan, 1990).

In this study, the Ghanaian clone SG224 and the Beninese clone BE203 with the highest male GCA effects, contributed to early nut yield, canopy spread and cropping efficiency. The positive GCA effects observed for these clones implied that they could possess favorable alleles for these traits and would be the source of genes of early nut yield, wider canopy spread and cropping efficiency. These finding were found to be in concurrence with the report by Adu-Gyamfi et al. (2019) who highlighted that the
Beninese clone could possess alleles for early nut yield, especially under sub-optimal field conditions. The alleles for high performance in the Ghanaian clone may be associated with the flexibility in response to biotic and abiotic stresses, unique to local germplasm clones (Carena, 2011).

On the other hand, the contribution of positive GCA effects by the Brazilian clone A2 and the Ghanaian clone SG273 for nut weight suggest that they could be a repository of genes for larger nuts. They could therefore be utilized as a donor of higher nut quality. The high performance of the Brazilian clone A2 for nut weight suggest that it might possesses genes for larger nut weight or “bolder nuts” and could be utilized in breeding programs to improve nut quality (Aliyu and Adedokun Awopetu, 2011). However, the negative GCA effects observed in A2 for nut yield and vigor and SG224 and SG287 for nut weight suggest that they had little contribution to additive gene action for these traits.

Interestingly, the significant negative GCA effect observed in SG287 and the positive GCA effects observed with SG266 for stem diameter increment at reproductive stage suggests SG287 partitioned small amount of assimilates to reproductive growth, while SG266 partitioned large amounts of assimilates to vegetative growth. Thus, SG287 could be utilized as a donor to improve cropping efficiency in cashew improvement programs. Earlier studies in cocoa (Theobroma cacao L.) reported similar observations (Padi et al., 2017). The relatively low variability (variance component due to females) recorded among the female parents for SDI (vegetative stage), nut yield, nut weight, height and cropping efficiency and male parents for SDI at the reproductive stage suggest that improving these traits in the future would require evaluating a wide array of both male and female parental clones with good combining ability.

The moderate narrow-sense heritability (>50%) estimates observed for vigor (estimated as stem diameter increment at the vegetative), early nut yield, nut weight and cropping efficiency implied that these traits were predominantly under the control of genetic effects and that considerable selection responses can be expected. Although heritability estimates for cropping efficiency is rare in cashew, the heritability estimates observed in this studies were comparable to those reported by in cashew by Cavalcanti et al. (2007b).

The moderate to high phenotypic correlations observed among the traits, except stem diameter increment at the reproductive stage in the current study suggest that selection for one of the traits could produce a favorable response in the other trait. The significant positive correlations observed between nut yield and canopy spread and height suggested that nut yield was positively affected by canopy spread and height. Thus, selecting for rapid increase in canopy spread and height could result in high early nut yield. However, the relatively strong significant correlation between nut yield and canopy spread ($r = 0.74, P < .01$) in the north-south direction could be a better indicator for determining early nut yield. These findings were in concurrence with other studies in cashew (Masawe et al., 1999; Sethi et al., 2016). The significant positive correlation between cropping efficiency and nut yield ($r = 0.92, P < .001$) also implied that selection for high cropping efficiency could be resulted in high yield. Generally, yield of a particular genotype varies with its size and cropping efficiency, these traits can be used as indirect selection for nut yield in cashew (Daymond et al., 2002; Padi et al., 2017).

**Conclusion**

The analysis of the combining abilities of the Brazilian, Beninese and Ghanaian clones evaluated in this study indicated that they had different merits as potential parents for vigor, early nut yield, nut weight and cropping efficiency. Overall, the development of cashew cultivars that combine high early nut yields with high nut quality is desirable. In comparison with the performance of existing clones recommended for farmers (Adu-Gyamfi et al. 2019), two types of progenies were identified. The first group was consisted of progenies with high early nut yield and moderate nut weight (7.2–7.4 g), such as SG287 × BE203, SG287 × SG273 and SG276 × SG224, while the second group composed of progenies with moderate early nut yielding (448–
563 kg ha\(^{-1}\)) and large nut weights (8.1–10.1 g), such as SG276 × SG224, SG276 × A2 and SG266 × A2. It is therefore imperative that the potential of these six F\(_1\) cashew progenies be validated in multi-location tests under farmers’ production conditions across the cashew production belt in the West African Sub-region. Additive effects played a dominant role in the inheritance of most of the traits, therefore, cashew improvement programs should be directed toward the selection of superior parents or good combiners, with an emphasis on GCA. The most useful clones identified in this study were the Ghanaian clone SG224 (significant positive GCA effects for early nut yield and canopy spread in the north-south direction), the Beninese clone BE203 (significant positive GCA effects for nut yield, cropping efficiency and canopy spread in the east west direction), the Brazilian clone A2 (significant positive GCA effects for nut weight) and the Ghanaian clone SG273 (significant positive GCA effects for vigor and nut weight). Selection to improve early nut yield should also concentrate on plants with wider canopies. Based on early nut yield and nut weight, the Brazilian, Beninese and Ghanaian clones represent a suitable genetic resource for cashew breeding.

**Acknowledgments**

The authors thank Mr Gabriel Boahen and the field staff of the Wenchi Agricultural Research Station and Bole-Substation for their support and assistance throughout this study. This manuscript is published with the kind permission of the Executive Director of Cocoa Research Institute of Ghana (CRIG) as manuscript number CRIG/011/2020/035/005.

**Disclosure Statement**

No potential conflict of interest was reported by the author(s).

**Funding**

The authors acknowledge the support of the German Government (GIZ) with funding through the African Cashew Initiative (ACI) and the Cocoa Research Institute of Ghana (CRIG); Deutsche Gesellschaft für Internationale Zusammenarbeit;

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