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# Combining ability and gene action for yield improvement in kenaf (*Hibiscus cannabinus* L.) under tropical conditions through diallel mating design

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Nine morphologically distinct kenaf genotypes were hybridized to produce 36 hybrids following a half diallel mating design. The combining ability and gene action of 15 yield and yield components were assessed in hybrids and their parents across two environments. Except for the mid diameter and plant height traits, there were highly significant differences ($p \leq 0.01$) between the environments and the interaction of genotype and environment. Additive gene effects were considerable for the inheritance of these traits, and the expression of these additive genes was heavily influenced by the environment. Significant differences were found for all studied traits for GCA except top diameter and SCA except plant height and top diameter, implying the presence of both additive and non-additive gene action for the inheritance of the concerned characters. For all features except top diameter and number of nodes, the magnitude of GCA variation was significantly higher than that of SCA variance, indicating the additive gene's predominance. The parental lines $P_1$, $P_3$ and $P_4$ were outstanding general combiners for fiber yield and yield-related parameters. Considering combining ability and genetic analysis study, the crosses $P_1 \times P_4$, $P_1 \times P_9$, $P_2 \times P_3$, $P_2 \times P_5$, $P_4 \times P_6$, $P_4 \times P_7$, $P_4 \times P_9$, $P_5 \times P_8$, and $P_7 \times P_9$ were found promising for their heterotic response to higher fiber yield, stick yield, seed yield and could be for future improvement in kenaf breeding programmes.

Fiber crops have been a part of human society from the beginning of time. Humans have been known to gather raw materials from the wild for use as ropes or textiles throughout history. Societies later learnt how to cultivate these types of crops. Natural fibre crops are among the earliest known cultivated plants, and humans have continued to domesticate and improve upon them throughout human history. Fiber crop types have been extensively developed through effective selection and breeding in response to the requirements and values of various communities around the world[50]. Kenaf (*Hibiscus cannabinus* L., Malvaceae) is a high-value fibre crop with significant economic value (Keshk et al. 2006). It is widely cultivated for food and fibre, and it has been extensively utilized as a cordage crop to produce twine, rope, sackcloth, coarse, burlap, and fiberboard[50]. Kenaf is grown commercially for a variety of purposes, including pulping and paper production, oil spill bioremediation, livestock feed, and the production of biodegradable packaging materials[25]. Kenaf seed is also commercially important because it is a good oil source (16–22%) lubrication, soap production, cosmetics, linoleum, paints, and varnishes[8,33].

In China, and India, hybrid kenaf cultivars accounted for most cultivated accessions[24]. Hybrid kenaf has received much attention due to its enhanced fiber quality and resistance to force[2]. Due to the ability of kenaf flowers to both self-pollinate and cross-pollinate, the crossover can range from 2 to 24%, depending on insect activity[4]. Dempsey[11] reported that the productivity of $F_1$ in kenaf ranges from 14 to 43% more than the parents. Compared to alternative mating designs, the diallel analysis is an effective method for screening parents for

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| Parent | Accession | Mode of development | Generation | Salient features |
|--------|-----------|---------------------|------------|------------------|
| $P_1$ | ML5 | Acute (300), MNA | $M_7$ | Late maturing cultivar with high fiber yielding green palmate leaves and completely cream flower color with white stigma |
| $P_2$ | ML9 | Acute (300), MNA | $M_7$ | Positive flowering attributes and deep green cordate leaves |
| $P_3$ | ML36-10 | Acute (300), MNA | $M_6$ | Cordate leaves are pale green in color and produce a lot of fiber and stick |
| $P_4$ | ML36-24 | Acute (1300), MNA | $M_6$ | Growing quickly and creating a lot of biomasses with high fiber and stick yield |
| $P_5$ | ML36-25 | Acute (1300), MNA | $M_6$ | Best performer for both seed yield traits (seeds number per pod and 1000 seeds weight) |
| $P_6$ | ML36-27 | Acute (1300), MNA | $M_6$ | Green stem with reddish patches and deep green cordate leaf |
| $P_7$ | BJRI Kenaf4 | Conventional method, BJRI | Check | Purple stem with palmate leaf that develops swiftly and produces several pods per plant |
| $P_8$ | MLRing4P2 | Chronic, MNA | $M_6$ | Bark thickness is comparatively low and the fiber to stick ratio is intermediate |
| $P_9$ | ML36-21(2) | Acute (800), MNA | $M_6$ | Green palmate leaves and are far less photosensitive |

**Table 1.** Origin and salient features of nine selected kenaf genotypes used as parents for diallel cross. *MNA* Malaysian Nuclear Agency, *BJRI* Bangladesh Jute Research Institute.

hybrid production. Different varieties of diallel crosses exist, however, in terms of the number of reciprocal crossings, half diallel crosses are more manageable for breeders than full diallel analysis[7]. Combining ability analysis is an effective tool for identifying superior hybrid parents with high general combining ability (GCA) and progenies with improved specific combining ability (SCA)[45]. It is also useful for measuring the genetic worth of parents and crossings in terms of gene activity in quantitative character inheritance and exploitation and breeding[13].

General combining ability (GCA) refers to a parent's average performance in a series of crossings. In contrast, SCA refers to a hybrid combination that is better or worse than expected based on the average performance of the parental inbred lines involved[6]. Parents with a high GCA effect have additive gene activity, but they do not always have a favorable SCA in their combination[38]. Meanwhile, determining the sort of gene action that affects the phenotypes of interest using SCA estimation is useful in genetic research. A high SCA identifies non-additive gene action[46]. When measured in terms of average effects (components), SCA effects were bigger than GCA effects, indicating the importance of non-additive gene activity in influencing yield component expression[32]. SCA and GCA data aid in selecting hybrids and parents for successful breeding[34]. Therefore, strong hybrids are produced by parents who have good GCA[41].

Heterosis is a genetic phenomenon caused by heterozygosity and is an important plant improvement measurement. Heterosis for fiber yield is well-known, and kenaf hybrid cultivars have been generated and used commercially in China[25]. The accumulation of dominant genes from both parents, according to Bruce[5], is linked to the development of dominance heterosis. Yang et al.[48] described epistasis as interactions among non-alleles on a genome, whereas Cordell[9] defined it as interactions between genes. Jianmin et al.[20] claimed that $F_1$ heterosis can survive 1.4–1.7 generations on average, but that favorable hybrids could last 3–4 generations. By selecting genotypes with distinct genetic backgrounds, it will be highly useful for improving the variety of kenaf in the Malaysian tropical environment[12]. The primary goal of this research was to identify genotypes (parents and offspring) with good combining ability that could assist future kenaf improvement with high fiber yield.

## Materials and methods

**Planting materials.** Nine kenaf genotype parents and 36 $F_1$ hybrids were employed in this study (Table 1). Among the nine genotypes, one was a commercial variety from Bangladesh and eight mutant lines were developed from V-36 through acute and chronic gamma irradiation by the Malaysian Nuclear Agency in Bangi, Selangor. The parents were mated in all possible combinations, barring reciprocals (half diallel) at Field 10 in University Putra Malaysia to produce 36 $F_1$ hybrids. The International Union for Conservation of Nature's (IUNC) statement on research involving species at risk of extinction and the convention on the trade in endangered species of wild flora and fauna were followed during the collection of plant materials and execution of the experiment. Table 1 contains a list of all of the accession numbers, along with their IDs codes.

**Hybridization techniques and raising of $F_1$ seeds.** Nine genotypes were chosen as parental materials and mated in diallel fashion omitting reciprocals, considering group distances, genetic distances, and other agronomic performance. To achieve flowering synchronization was observed during the crossing period where pure and healthy seeds were sown in the experiment field three times at 10-day intervals. The $F_1$ seeds were collected after the fruits had ripened, using standard methods for emasculation and pollination.

**Experimental location.** The experiment plots were conducted in two seasons in a humid tropical climate between latitude 2° 59′ N and longitude 101° 42′ E, at 48 m above sea level at Field 10, Universiti Putra Malaysia (UPM), Serdang, Selangor Darul Ehsan. The first season was conducted from June 2020 to September 2020, while the second was from March 2021 to June 2021.

**Experimental design and field layout.** The field was mechanically ploughed and laddered for cultivation. Kenaf seeds from 45 entries, consisting of nine parents and 36 $F_1$s were planted in peat moss soil in germination trays at a glasshouse for two weeks before being transplanted into the field plots of 59 m × 9 m. The experiment was laid out in Randomized Complete Block Design (RCBD) with three replications using a table

| Quantitative trait | Abbreviation (unit) | Description of evaluation method |
|---|---|---|
| Plant height | PH (cm) | Plant height was measured from the base to the tip of the main shoot of 10 randomly selected plants in meter scale at the time of harvest (pre-bud stage, 90 DAS) |
| Base diameter | BD (mm) | Average base diameter of 10 randomly selected plants was measured at the base of the stem in mm using slide calipers |
| Core diameter | CD (mm) | It was measured at the base point of the stem using slide calipers after the fiber separated from the stem. It was taken at the end of retting period |
| Middle diameter | MD (mm) | It was measured at the mid-point between base and top of the stem using slide calipers. It was also taken at the time of harvest |
| Top diameter | TD (mm) | It was measured at the top of the stem using slide calipers. It was also taken at the time of harvest |
| Number of nodes | NN | Number of nodes of 10 randomly selected plants was counted and averaged then for getting node no/plant |
| Days to first flowering | DTFF (days) | It was recorded as the number of days from the date of sowing to beginning of flowering in the population of each genotype |
| Days to 50% flowering | D50%F (days) | The number of days to flowering was quantified from planting date to the day when 50% flowering in the population of each genotype |
| Fresh stem weight with leaves and pods | FW1 (g) | Average fresh stem weight with leaves and pods of 10 plants was recorded using electric balance just after harvest and then per plant basis weight was calculated |
| Fresh stem weight without leaves and pods | FW2 (g) | Fresh stem weight of 10 randomly selected plants without leaves and pods was taken using electric balance just after harvest and then per plant basis weight was calculated |
| Dry stick weight | DSW (g) | It was measured from 10 previously selected plants after extraction of fiber and proper sun drying of the stick and the mean was computed |
| Dry fiber weight | DFW (g) | Dry fiber weight of randomly selected 10 plants from each plot was taken after retting and proper drying in the sun. Finally, per plant basis weight was calculated |
| Number of pods per plant | NF | Number of total pods from first to last pod setting per plant was counted in the field and recorded |
| Number of seeds per pod | NS | Number of matured seeds from 30 randomly selected pods per replication was counted and it was then averaged and replication wise recorded |
| 1000 seeds weight | SW (g) | Weight of 1000 dry seeds (10% moisture) of each genotype for each replication was measured using digital balance and recorded |

**Table 2.** Quantitative characters studied from nine parents and their crosses.

of random numbers[15]. NPK Green (15:15:15) and NPK Blue (12:12:17) were applied at the prescribed dose of 450 kg per hectare shortly after seeding and after 40 days of transplanting. Intercultural operations like weeding, thinning, supplemental irrigations, and plant protection measures were performed appropriately throughout the cropping season.

**Data collection.** The genetic diversity was assessed using 22 features (seven qualitative and 15 quantitative) related to the plant, flower, fiber yield, pod, and seed across two seasons. The observation was recorded from 10 randomly selected plants for each genotype per replication for each trait. The qualitative traits, including stem color and leaf shape were visually recorded at seedling and growth stages in the field. Leaf color, petiole color, pod shape, seed shape and seed coat color were visually recorded at the pre-bud and mature stages. Quantitative data collected include plant height, base diameter, core diameter, middle diameter, top diameter, nodes number, days to first flowering, days to 50% flowering, fresh stem weight with leaves and pods, fresh stem weight without leaves and pods, dry stick weight, dry fiber weight, pods number per plant, seeds number per pod and 1000 seeds weight (Table 2). Days to first flowering, days to 50% flowering, and pods number per plant were all verified in the field, and residual traits were measured in the lab 90 days after transplanting[3].

**Statistical analysis.** Combined analysis of variance (ANOVA) was performed on all data to assess the amount of variability present among parents and their offspring using SAS (Statistical Analysis Software) version 9.4 (SAS Institute Inc., Cary, NC, USA). The mean performances of hybrids and paternal inbred lines were compared using the Least Significant Difference (LSD) method at a 5% level of significance. The general combining ability of parents and specific combining ability of hybrids were determined following Griffing's method 2 model 1 using SAS software according to Zhang and Kang[51].

**Estimation of heterosis.** The relative heterosis (MP) and heterobeltiosis (BP) were determined and expressed as percentages[26]. The amount of heterosis was calculated using the differences between the mean of $F_1$ hybrids and the mid parental value for a given characteristic[37].

i. Mid-parent heterosis = [($F_1$ − MP)/MP] × 100 (relative heterosis).
Where, $F_1$ is the mean value of the $F_1$, MP is the mean value of two parental involves in $F_1$ i.e. $(P_1 + P_2)/2$. The significance of relative heterosis was tested using t-test[47].

$$t = F_1ij - MPij/(3/8\sigma e)^{1/2},$$

where, $F_1ij$ is the mean of the ijth $F_1$ cross, $MPij$ is the mid-parent value for ijth cross, $\sigma^2 e$ is the estimate of error variance.

ii. Better parent heterosis = [($F_1$ − BP)/BP] × 100 (heterobeltiosis).

Where, $F_1$ is the mean value of the $F_1$, BP is the mean value of better parent.

The significance of relative heterosis was tested using t-test[47].

$$t = F_1ij - BPij/(1/2\sigma_e^2)^{1/2},$$

where, $F_1ij$ is the mean of the ijth $F_1$ cross, BPij is the Better value for ijth cross, $\sigma_e^2$ is the estimate of error variance.

## Result

**Qualitative variation.**     Qualitative characteristics assessment provides information on highly diverse or uniform character, which can be quite different or very consistent (Table 3). Figures 1, 2 and 3 show the variation observed among the seven qualitative traits, revealing that plant, stem and leaf characteristics differed significantly.

**Parents.**     The selected parents' stem color, leaf shape, leaf color (lamina), and petiole color varied greatly. Two of the nine parents, $P_1$ and $P_2$, were green stem types with green petioles. Parent $P_7$ had a light reddish upper surface but a green petiole on the lower surface with a purple stem. Otherwise, five parents ($P_3$, $P_4$, $P_5$, $P_6$, and $P_8$) had green petioles with cordate leaves and green stems with reddish patches. Palmate leaf morphologies with green leaf colors were seen in parents $P_1$, $P_7$, and $P_9$ (Table 3). Parents $P_2$, $P_4$, $P_6$, and $P_8$ had deep green leaves, whereas $P_3$ had pale green leaves. The genotypes are further divided into three groups depending on pod shape: globular (round), elongated (pointed), and oval (egg-shaped). Genotypes differed in seed shape and seed coat colors. The parent $P_4$ seed coat color were brownish, while the $P_6$ seeds were black with a few brownish patches and the rest were ash gray.

**$F_1$ generation.**     The stem color showed a lot of variances with standard error (Sem, ± 5.17) (Fig. 1). The color variance for the green with reddish patches, green, reddish above greenish below, reddish, purple, and red stem colors was 41.67%, 16.67%, 13.89%, 11.11%, 8.33%, and 8.33%, respectively (Fig. 4a), from the 36 described kenaf $F_1$ hybrids. Palmate leaves were found in 55.56% of $F_1$ hybrids, whereas cordate leaves were found in 44.44% (Fig. 4b). The 36 $F_1$ hybrids' leaf color (lamina) was diverse, falling into three categories: green, deep green, and pale green, which accounted for 72.22%, 25.00%, and 2.78% genotypes, respectively (Figs. 2 and 4c). Petiole color varied greatly among the hybrids investigated, with 72.22%, 22.22%, 2.78%, and 2.78% for green, upper surface light reddish but lower green, reddish, and purple, respectively (Fig. 4d). The form of the kenaf pod also showed a wide range of variation with standard error (Sem, ± 14.26). The genotypes are divided into three groups based on pod shape: globular (round) 52.78%; ovoid (egg-shaped) 41.67%; and elongated (pointed) 5.55% (Figs. 3 and 4e). Seed shape and seed coat color differed across the 36 $F_1$ hybrids. Triangular seed shape was found in 80.56% of $F_1$ hybrids, whereas sub-reniform seed shape was found in 19.44% (Fig. 4f). Blackish seeds were found in up to 41.67% of hybrids, ash gray seeds in 38.89%, brownish seeds in 13.89%, and black with few brownish color seeds in 5.55% (Fig. 4g).

**Variation among all genotypes for quantitative traits in pooled environments.**     Across the two environments, the combined analysis of variance for the 15 quantitative features among the nine parents and 36 crosses revealed significant differences (Table 4). There were significant differences ($p \leq 0.01$) in environments and genotypes (parents and offspring) for all the variables studied, with exception of middle and top diameter, respectively. There were significant variations ($p \leq 0.01$ or 0.05) for genotype by environment (G × E) except for plant height. Base diameter, core diameter, middle diameter, top diameter, number of nodes, days to 50% flowering, fresh stem weight with leaves and pod, fresh stem weight without leaves and pod, dry stick weight, dry fiber weight, number of pods per plant, number of seeds per pod, and 1000 seed weight were all shown to be highly significant differences ($p \leq 0.01$) for G × E interactions. The CV% for yield and yield-related components ranges from 9.40 (days to 1st flowering) to 69.05 (nodes number), showing that the evaluated traits have a wide variability range.

**Variation among all genotypes due to combining ability effects in pooled environments.**     Analysis of variance for combining ability using Griffing's (1956) technique was utilized for all analyzed qualities in the $F_1$ combined data (Table 5) for both environments. General combining ability (GCA) is generally understood to be a consequence of additive gene effects and additive epistatic variance components. Specific combining ability (SCA), on the other hand, is a result of non-additive gene effects and the remaining epistatic variation (Matzinger et al., 1959). The mean squares analysis of variance results for the effects of combining ability are shown in Table 5. Significant differences ($p \leq 0.01$ or 0.05) were observed for all studied traits for GCA except for top diameter and SCA except for plant height and top diameter, indicating the presence of both additive and non-additive gene action for the inheritance of the concerned characters. Except for plant height, and fresh stem weight without leaves and pod, significant differences ($p \leq 0.01$ or 0.05) were reported for the interaction between GCA and environment. Except for plant height, top diameter, and days to first flowering, all traits showed significant variations ($p \leq 0.01$ or 0.05) when SCA and environment interacted. Thus, the effects of non-additive genes in the traits interacted more with the environment. GCA and SCA ratios ranged from 0.54 (nodes number) to 8.29 (days to first flowering). For top diameter, nodes number, and fresh stem weight with leaves and pod, the ratio of GCA and SCA variances was found to be smaller than unity, indicating that non-additive gene action predominated. The estimated GCA/SCA was greater than unity for the other characters, indicating that additive gene effects predominated in their expression. In kenaf, Jianmin et al.[20] and Heliyanto et al.[18] found similar results.

| Parents/hybrids | Stem color | Leaf shape | Leaf color (lamina) | Petiole color | Pod shape | Seed shape | Seed coat color |
|---|---|---|---|---|---|---|---|
| $P_1$ | Green | Palmate | Green | Green | Ovoid | Triangular | Ash gray |
| $P_2$ | Green | Cordate | Deep green | Green | Ovoid | Triangular | Ash gray |
| $P_3$ | Grp | Cordate | Pale green | Green | Ovoid | Triangular | Ash gray |
| $P_4$ | Grp | Cordate | Deep green | Green | Ovoid | Sub-reniform | Brownish |
| $P_5$ | Grp | Cordate | Green | Green | Globular | Triangular | Ash gray |
| $P_6$ | Grp | Cordate | Deep green | Green | Elongated | Triangular | Bfb |
| $P_7$ | Purple | Palmate | Green | UrLg | Ovoid | Triangular | Ash gray |
| $P_8$ | Grp | Cordate | Deep green | Green | Globular | Triangular | Ash gray |
| $P_9$ | Grp | Palmate | Green | Green | Elongated | Triangular | Ash gray |
| $P_1 \times P_2$ | RaGb | Palmate | Green | Green | Ovoid | Sub-reniform | Blackish |
| $P_1 \times P_3$ | Reddish | Palmate | Green | Green | Ovoid | Triangular | Blackish |
| $P_1 \times P_4$ | Reddish | Palmate | Green | Green | Ovoid | Triangular | Ash gray |
| $P_1 \times P_5$ | RaGb | Palmate | Green | Green | Ovoid | Triangular | Brownish |
| $P_1 \times P_6$ | RaGb | Palmate | Green | Green | Elongated | Sub-reniform | Blackish |
| $P_1 \times P_7$ | Purple | Palmate | Deep green | UrLg | Globular | Triangular | Ash gray |
| $P_1 \times P_8$ | RaGb | Palmate | Green | Green | Globular | Triangular | Ash gray |
| $P_1 \times P_9$ | RaGb | Palmate | Green | Green | Globular | Triangular | Ash gray |
| $P_2 \times P_3$ | Grp | Cordate | Deep green | Reddish | Globular | Sub-reniform | Blackish |
| $P_2 \times P_4$ | Grp | Cordate | Green | Green | Ovoid | Sub-reniform | Ash gray |
| $P_2 \times P_5$ | Grp | Cordate | Green | Green | Elongated | Triangular | Blackish |
| $P_2 \times P_6$ | Grp | Cordate | Green | Green | Ovoid | Triangular | Blackish |
| $P_2 \times P_7$ | Purple | Palmate | Deep green | UrLg | Globular | Triangular | Ash gray |
| $P_2 \times P_8$ | Grp | Cordate | Green | Green | Globular | Sub-reniform | Ash gray |
| $P_2 \times P_9$ | Green | Palmate | Deep green | Green | Ovoid | Triangular | Ash gray |
| $P_3 \times P_4$ | Green | Cordate | Green | Green | Globular | Triangular | Blackish |
| $P_3 \times P_5$ | Green | Cordate | Green | Green | Globular | Triangular | Blackish |
| $P_3 \times P_6$ | Grp | Cordate | Green | Green | Globular | Triangular | Ash gray |
| $P_3 \times P_7$ | Reddish | Palmate | Green | UrLg | Globular | Triangular | Bfb |
| $P_3 \times P_8$ | Grp | Cordate | Green | Green | Globular | Triangular | Ash gray |
| $P_3 \times P_9$ | Green | Palmate | Green | Green | Globular | Triangular | Blackish |
| $P_4 \times P_5$ | Green | Cordate | Deep green | Green | Globular | Triangular | Ash gray |
| $P_4 \times P_6$ | Green | Cordate | Deep green | Green | Globular | Triangular | Ash gray |
| $P_4 \times P_7$ | Purple | Palmate | Deep green | UrLg | Ovoid | Sub-reniform | Brownish |
| $P_4 \times P_8$ | Grp | Cordate | Green | Green | Ovoid | Triangular | Ash gray |
| $P_4 \times P_9$ | Grp | Palmate | Green | Green | Ovoid | Triangular | Blackish |
| $P_5 \times P_6$ | Grp | Cordate | Green | UrLg | Ovoid | Triangular | Brownish |
| $P_5 \times P_7$ | Red | Palmate | Deep green | UrLg | Globular | Triangular | Brownish |
| $P_5 \times P_8$ | Grp | Cordate | Green | Green | Ovoid | Triangular | Blackish |
| $P_5 \times P_9$ | Grp | Palmate | Pale green | Green | Ovoid | Triangular | Blackish |
| $P_6 \times P_7$ | Reddish | Palmate | Green | UrLg | Globular | Triangular | Ash gray |
| $P_6 \times P_8$ | Grp | Cordate | Deep green | Green | Globular | Triangular | Blackish |
| $P_6 \times P_9$ | Grp | Palmate | Green | Green | Globular | Triangular | Blackish |
| $P_7 \times P_8$ | Red | Cordate | Green | Purple | Ovoid | Triangular | Bfb |
| $P_7 \times P_9$ | Red | Palmate | Green | UrLg | Globular | Triangular | Brownish |
| $P_8 \times P_9$ | Grp | Palmate | Green | Green | Ovoid | Sub-reniform | Blackish |

**Table 3.** Characteristics of selected parents' growth stages and the $F_1$ kenaf population. *Grp* Green with reddish patches, *RaGb* Reddish above greenish below, *UrLg* Upper surface light reddish but lower surface green, *Bfb* Black with few brownish.

**Mean performance of genotypes over two environments.** The mean comparison for all genotypes (parents and offspring) was presented in Table 6. Plant heights ranged from 219.58 to 297.85 cm, with hybrid $P_3 \times P_7$ having higher mean value and $P_2 \times P_9$ recorded the lowest. The base diameter ranged from 19.95 mm ($P_2 \times P_9$) to 31.68 mm ($P_2 \times P_3$), but the base diameters of $P_1 \times P_9$ and $P_7 \times P_8$ were comparable. The $P_2 \times P_3$ had the largest core diameter (28.43 mm), while $P_2 \times P_9$ had the smallest (16.83 mm). The middle diameter was 9.69 mm ($P_2$) to 15.74 mm ($P_5 \times P_8$), with the maximum and lowest top diameters of $P_6 \times P_7$ and $P_1 \times P_7$, respectively. The hybrid $P_6 \times P_9$ had the most nodes (9.68), while $P_2$ had the least (4.15). Days to first flowering ranged from 43 to
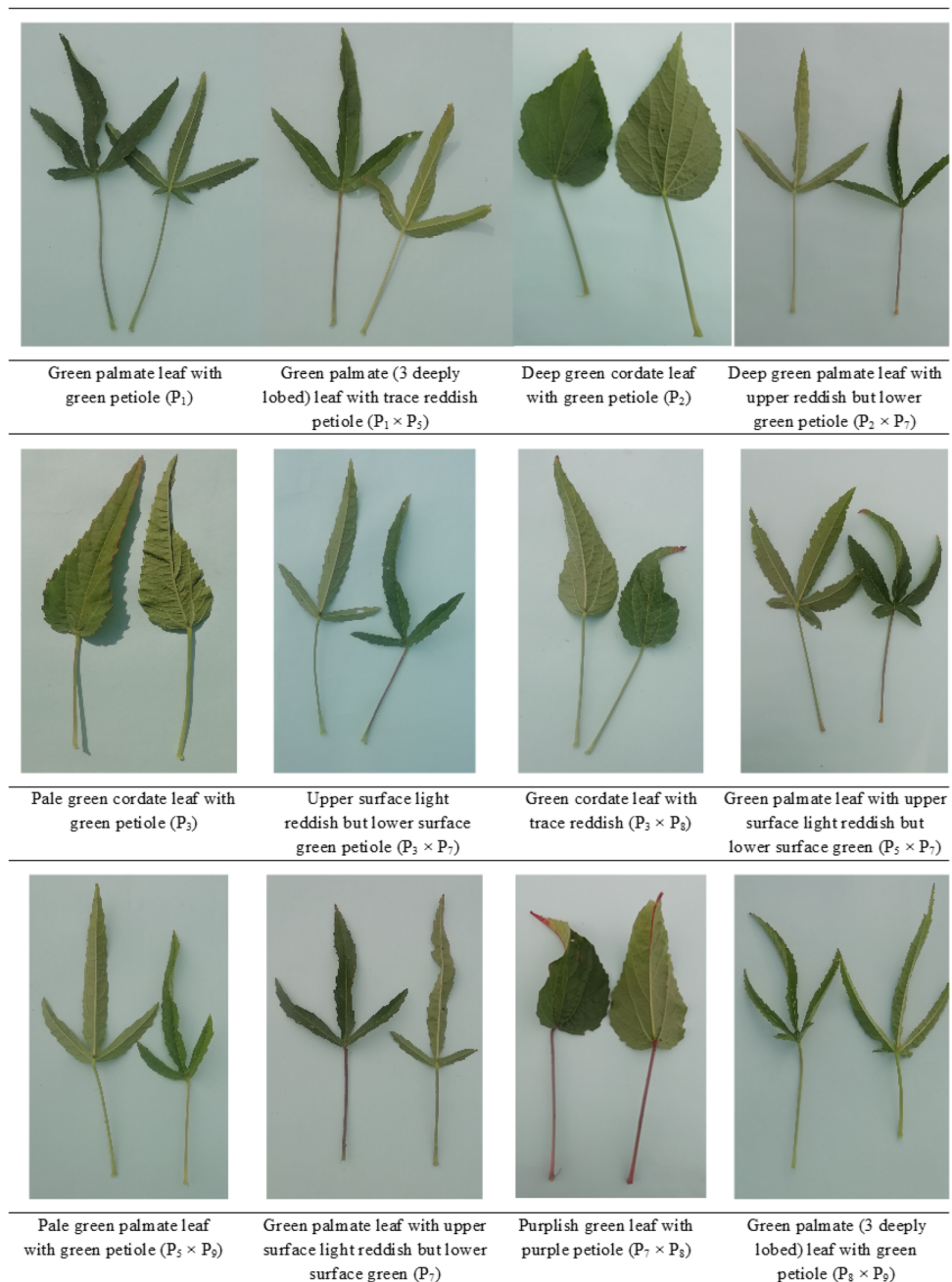
**Figure 1.** Photographs of the parents' and $F_1$ population for stem coloration (70 DAS).

56.33 days in $P_7 \times P_9$ and $P_2 \times P_5$, respectively. Days to 50% flowering ranged from 51 to 69.17 days. The hybrid $P_7 \times P_9$ was the first to mature, while parent $P_2$ was the last to mature (Table 6).

Fresh stem weight with leaves and pods ranged from 584.30 g ($P_2 \times P_9$) to 1786.50 g ($P_4 \times P_6$), with the highest and lowest fresh stem weight without leaves and pods being 449.96 g ($P_4 \times P_9$) and 222.41 g ($P_6$), respectively. The dry stick weight ranged from 71.35 to 152.93 g, with $P_1 \times P_4$ having the highest mean value (152.93 g), followed by $P_4 \times P_9$ (147.69 g), and $P_6$ having the lowest mean value (71.35 g). The hybrid $P_2 \times P_3$ yielded its most dry fiber weight per plant (38.74 g), whereas $P_7$ yielded the least (16.3 g). Aside from that, the hybrid $P_7 \times P_9$ produced the most pods per plant (217.15), whereas $P_2$ had the least (50.82). The number of seeds per pod ranged from 15.08 to 28.76. Parent $P_5$ had the most seeds per pod, while $P_1 \times P_2$ and $P_2 \times P_8$ contained the fewest. The weight of 1000 seeds varied from 26.20 to 35.05 g. The hybrid $P_2 \times P_8$ had the highest 1000 seed weight (35.05 g), while hybrid $P_1 \times P_5$ had the lowest 1000 seed weight (26.20 g) (Table 6).

Plant height, base diameter, core diameter, middle diameter, top diameter, number of nodes, fresh stem weight with leaves and pod, fresh stem weight without leaves and pod, dry stick weight, dry fiber weight, and pods number per plant are all higher than parental mean. In comparison to the hybrid mean, the parental mean has somewhat longer days to first flowering and days to 50% flowering. Similarly, the parental mean had more seeds per pod and 1000 seed weight than the hybrid means. The fact that the hybrid mean has a lower weight per 1000 seeds than the parental mean is advantageous because it allows for smaller seed sizes. The largest standard deviation (SD) value was observed for fresh stem weight with leaves and pod (518.40) with standard error (Sem, ± 31.55), while the lowest was for top diameter (SD, 1.92; Sem, ± 0.12) (Table 6). The standard error

**Figure 2.** Photographs of the parents' and F$_1$ population for leaf shapes and coloration.

(SE) indicates consistency of the average values, lower SE values suggest that the sample mean is a more precise depiction of the true population mean.

### Combining ability effects on genotypes (parents and offspring).

*General combining ability effects on genotypes (parents and offspring) in pooled environment.* Estimates of GCA effects of individual parental genotypes in the F$_1$ generation were found to be statistically significant or highly significant for most traits studied. Plant height in a taller stature combination should have a positive GCA effect, while the nodes number should have a negative GCA effect. In the pooled data, the parent P$_7$ had the maximum plant height (11.99 cm) and the lowest negative GCA values for nodes number (− 0.39), indicating that they were good general combiners for quality fiber yield and might be used in future breeding efforts. In terms of base diameter (2.32), core diameter (2.12), middle diameter (0.80), fresh stem weight with leaves and pod (176.17), fresh stem weight without leaves and pod (59.86), dry stick weight (16.57), and dry fiber weight (3.53), parent P$_4$ had the greatest positively significant GCA effect. Excluding the P$_4$, parent P$_1$ (2.00) and P$_3$ (1.89) were also shown to be positive and significant general combiners for dry fiber weight, with parent P$_3$ having a positive and highly significant GCA effect (15.09) for dry stick weight.
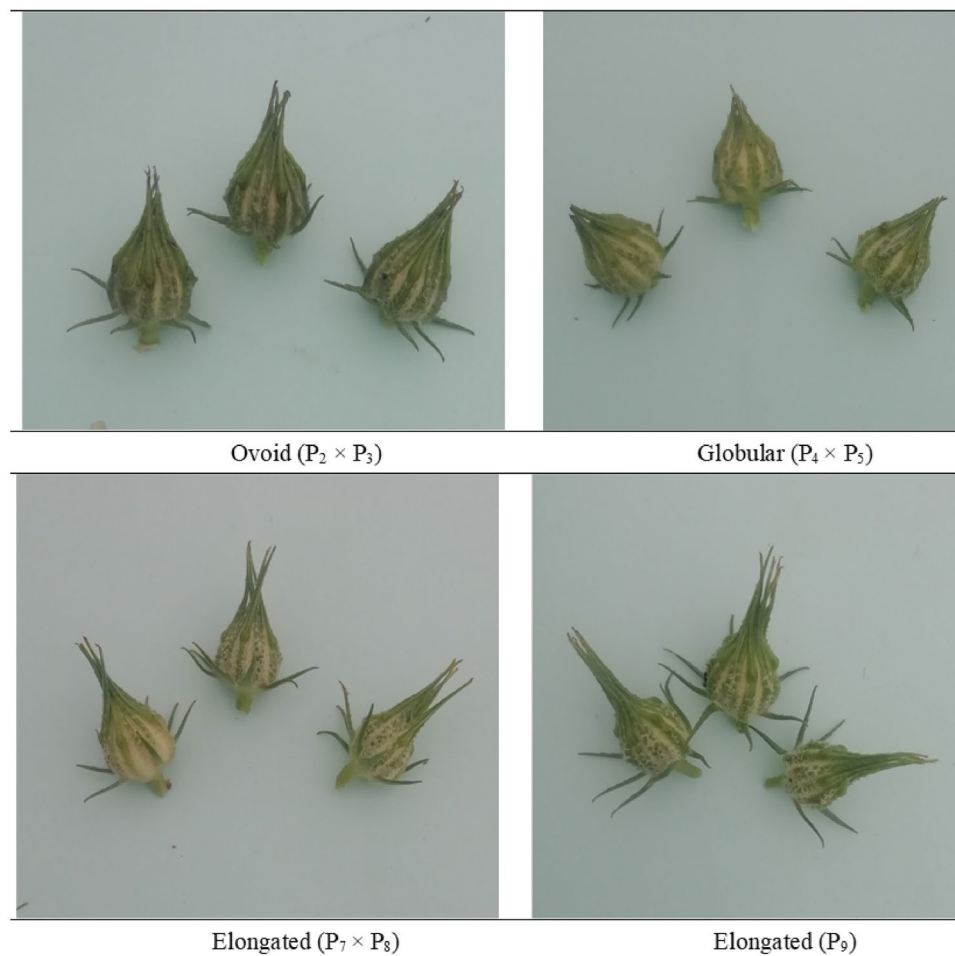
**Figure 3.** Photographs of the parents' and F$_1$ population for pod shapes and colors.

The parents P$_1$ (9.02), P$_6$ (12.76), and P$_7$ (17.57) had much higher seed output, which is a critical element in determining the pods number per plant. The parent P$_2$ had the most positively significant GCA effect, with values of 2.32 and 3.17 for days to 1st flowering and days to 50% flowering, respectively. With − 3.74 and − 3.71, respectively, for days to first flowering and days to 50% flowering, parent P$_7$ had the smallest GCA effect (Table 7). The parent P$_2$ showed the lowest negative and highly significant GCA effect, with values of − 17.73, − 140.47, − 18.64, and − 4.50 for plant height, fresh stem weight with leaves and pod, pods number per plant, and seeds number per pod, respectively. For base diameter (− 2.34), core diameter (− 2.49), and fresh stem weight without leaves and pods (− 64.18), the parent P$_9$ exhibited the lowest negative GCA values. A negative GCA effect is desired for 1000 seed weight to give a smaller seed size combination. The parent P$_5$ had the most desirable 1000 seed weight with a negative GCA effect (− 1.63) and the highest positive (1.36) for seeds number per pod, both of which are highly significant, indicating that they were good general combiners for reduced seed sizes and the highest seeds number per pod in future breeding programs.

**Specific combining ability effects on hybrids across the environment.** The effects of specific combining ability on hybrids in various contexts in pooled environments are shown in Table 8. SCA effects were detected in all 36 hybrids studied, with positive (desired direction) SCA influences on plant height in 19 of them. The hybrid with significant and beneficial SCA effects were produced by the cross P$_5$ × P$_8$ (24.44), which was evaluated as a good specific combiner for tallness. The hybrids P$_1$ × P$_5$ (− 23.51) and P$_2$ × P$_9$ (− 37.62) were identified as the worst specific combiners for this trait, as shown by the significant negative SCA effects for plant height. The SCA effects on the base diameter ranged from − 6.33 to 5.47. Three of the 16 positive SCA effects for base diameter on the were found to be best specific combiners with highly significant (P$_2$ × P$_3$, P$_4$ × P$_6$ and P$_5$ × P$_8$), while two were found to be good specific combiners with significant (P$_1$ × P$_7$ and P$_7$ × P$_9$). Other 20 crosses had negative SCA effects, including one (P$_2$ × P$_9$) with a highly significant SCA value of − 6.33.

Out of 36 cross combinations, five showed significant positive SCA values for kenaf core diameter, indicating heterotic performance over the mean of their parents. The cross P$_2$ × P$_3$ had the highest positive SCA effect (5.81), followed by P$_5$ × P$_8$, P$_7$ × P$_9$ and P$_4$ × P$_6$, indicating that they were the best specific combiners for the trait. The cross P$_2$ × P$_9$ had the most negative and highly significant SCA effect (− 5.86) and was considered the worst
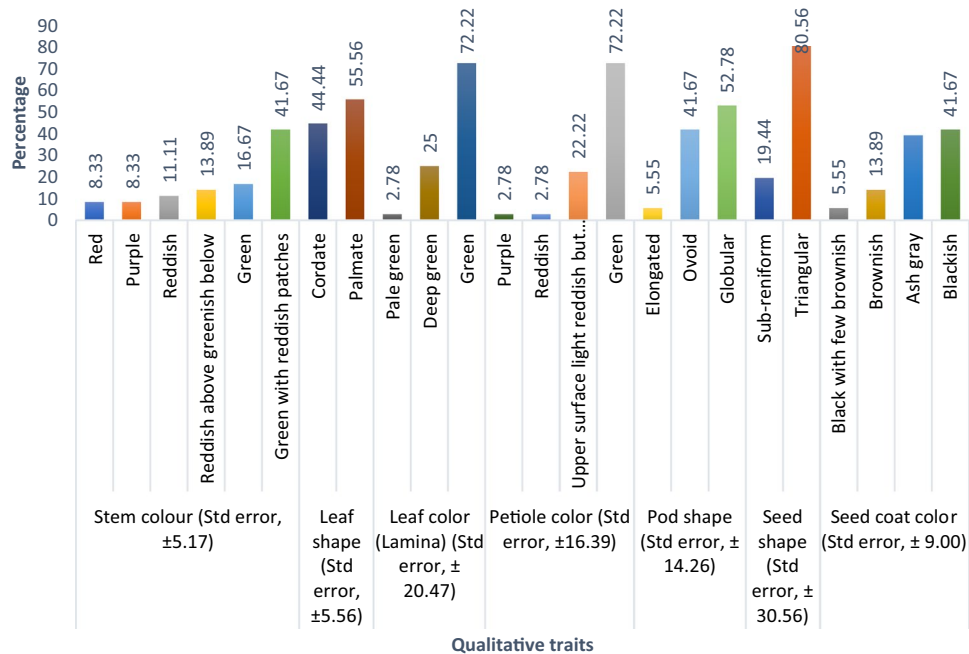
**Figure 4.** Qualitative variation in the kenaf $F_1$ population (**a**) Stem color, (**b**) Leaf shape, (**c**) Leaf color (lamina), (**d**) Petiole color, (**e**) Pod shape, (**f**) Seed shape, and (**g**) Seed coat color.

| Traits | Reps (environment) | Environments (E) | Genotypes (G) | G × E | Error | CV |
|---|---|---|---|---|---|---|
| DF | 4 | 1 | 44 | 44 | 176 | |
| PH | 1315.93 | 47,673.09** | 1814.32** | 769.20 | 644.08 | 12.02 |
| BD | 53.89** | 2644.85** | 45.51** | 28.09** | 7.80 | 20.39 |
| CD | 60.42** | 2716.06** | 42.49** | 30.47** | 7.73 | 23.81 |
| MD | 128.33** | 3.95 | 7.08** | 4.75** | 2.18 | 19.19 |
| TD | 42.75** | 534.31** | 1.24 | 1.59** | 0.92 | 44.68 |
| NN | 2.27 | 5677.56** | 10.16** | 9.65** | 2.28 | 69.05 |
| DTFF | 76.69** | 258.13** | 54.04** | 19.53* | 12.34 | 9.40 |
| D50%F | 122.47** | 1946.76** | 85.63** | 59.30** | 33.12 | 12.55 |
| FW1 | 4918.52 | 18,630,479.18** | 466,505.69** | 488,941.97** | 65,920.85 | 42.00 |
| FW2 | 42,044.66** | 471,710.49** | 19,213.80** | 10,701.47** | 4361.17 | 30.88 |
| DSW | 3601.17** | 18,465.68** | 2344.96** | 3071.62** | 877.24 | 36.86 |
| DFW | 4.60 | 5968.64** | 126.22** | 102.29** | 17.80 | 33.59 |
| NF | 3921.87** | 80,067.83** | 6548.07** | 5281.92** | 646.90 | 43.81 |
| NS | 12.62** | 1966.57** | 77.45** | 49.12** | 3.60 | 23.48 |
| SW | 0.97 | 2595.63** | 23.57** | 20.64** | 1.46 | 13.52 |

**Table 4.** Combined analysis of variance was performed for 15 quantitative attributes of nine parents and their crosses over two environments. *CV* coefficient of variation, *DF* degree of freedom, *PH* plant height, *BD* base diameter, *CD* core diameter, *MD* middle diameter, *TD* top diameter, *NN* number of nodes, *DTFF* days to first flowering, *D50%F* days to 50% flowering, *FW1* fresh stem weight with leaves and pod, *FW2* fresh stem weight without leaves and pod, *DSW* dry stick weight, *DFW* dry fiber weight, *NF* number of pods per plant, *NS* number of seeds per pod, *SW* 1000 seeds weight. **Highly significant at $P \leq 0.01$ level, *Significant at $P \leq 0.05$ level.

specific combiner for core diameter. The SCA effects for mid-diameter stem varied from − 1.60 to 2.88. The hybrid $P_5 \times P_8$ had the best SCA effects with highly significant, while another 18 crosses had positive but insignificant SCA values, implying that they could be used as average specific combiners. Other 17 crossings had negative SCA effects, with one ($P_1 \times P_5$) being highly significant (− 1.60) and another ($P_6 \times P_8$) being significant (− 1.31). These are considered the worst specific combiners for mid-diameter (Table 8).

The SCA effects on top diameter ranged from − 0.75 to 1.10. Since four crossings revealed significant positive SCA effects, one of which was highly significant, $P_2 \times P_9$, $P_4 \times P_7$ and $P_5 \times P_8$ and $P_6 \times P_7$ were chosen as good

| Traits | GCA | SCA | GCA*ENV | SCA*ENV | GCA/SCA |
|---|---|---|---|---|---|
| Plant height | 5893.40** | 835.22 | 800.55 | 766.61 | 7.06 |
| Base diameter | 64.04** | 40.46** | 19.28* | 29.96** | 1.58 |
| Core diameter | 53.48** | 39.65** | 22.09** | 32.30** | 1.35 |
| Middle diameter | 15.73** | 5.19** | 8.07** | 4.01** | 3.03 |
| Top diameter | 1.14 | 1.31 | 2.50** | 1.40* | 0.87 |
| Number of nodes | 5.94* | 11.11** | 8.55** | 10.30** | 0.53 |
| Days to 1st flowering | 188.16** | 23.08** | 36.03** | 14.90 | 8.15 |
| Days to 50% flowering | 240.02** | 49.77* | 63.39 | 56.44* | 4.82 |
| Fresh stem weight with leaves and pod | 470,219.89** | 468,542.91** | 576,405.65** | 463,451.47** | 0.99 |
| Fresh stem weight without leaves and pod | 45,353.95** | 13,576.78** | 4757.88 | 12,033.75** | 3.34 |
| Dry stick weight | 5584.33** | 1730.88** | 2809.31** | 2782.49** | 3.23 |
| Dry fiber weight | 240.33** | 104.98** | 55.59** | 111.88** | 2.29 |
| Number of pods per plant | 9185.14** | 5590.47** | 4864.76** | 5587.88** | 1.64 |
| Number of seeds per pod | 51.31** | 17.65** | 47.78** | 14.09** | 2.91 |
| 1000 seeds weight | 240.64** | 41.05** | 24.73** | 55.12** | 5.86 |

**Table 5.** Mean squares of analysis of variance for combining ability of the 15 traits in pooled environments. *GCA* general combining ability, *SCA* specific combining ability, *GCA × ENV* interaction of GCA and environment, *SCA×ENV* interaction of SCA and environment. *Significant at P ≤ 0.05, **highly significant at at P ≤ 0.01.

specific combiners for this trait. The SCA values of another 15 crosses were positive but not significant, indicating that they may be regarded as average specific combiners for top diameter. SCA impacts ranged from − 4.15 to 2.39 for a given number of nodes. Hybrid $P_2 \times P_9$ (− 4.15) had the highest negative and highly significant SCA estimate, followed by $P_3 \times P_9$ (− 2.86), $P_4 \times P_9$ (− 2.71), and $P_1 \times P_9$ (− 2.38), with one negative significant $P_7 \times P_8$ (− 1.13), showing that these hybrids had good SCA for lower branch stem and improved fiber yield. Three of the 21 positive SCA effects, on the other hand, were found to be highly significant, and three were found to be significant, therefore they were classified as poor specific combiners for nodes number.

The SCA effects ranged from − 3.32 to 4.10 for days to first flowering (Table 8). The cross ($P_2 \times P_5$) was positively highly significant, with two more significant hybrids ($P_4 \times P_8$ and $P_1 \times P_9$), showing that these hybrids had good SCA for this trait. In contrast, the offspring $P_4 \times P_6$ exhibited the highest negative and significant SCA estimate, followed by $P_2 \times P_8$, all of whom were considered poor specific combiners for the days to first flowering trait. SCA impacts ranged from − 5.71 to 7.44 for days to 50% flowering. The cross $P_6 \times P_9$ of the 15 positive SCA effects, which displayed a good specific combining capacity for this characteristic, had the most significant SCA effects followed by $P_2 \times P_5$. Instead, the crosses $P_2 \times P_6$, $P_2 \times P_7$ and $P_4 \times P_6$ had the most negative and significant SCA estimates, indicating that they were poor specific combiners for days to 50% flowering.

Four crosses viz. $P_2 \times P_3$, $P_4 \times P_5$, $P_4 \times P_6$ and $P_5 \times P_8$ were the best specific combiners for fresh stem weight with leaves and pod trait, with highly significant positive SCA effects. Five more crossings of the 20 positive SCA effects viz. $P_1 \times P_3$, $P_1 \times P_7$, $P_2 \times P_7$, $P_3 \times P_5$ and $P_7 \times P_9$ produced positive and significant SCA effects, making them good specific combiners. Four of the remaining 16 crosses had significant SCA values, indicating negative SCA effects. As a result, they were regarded as poor specific combiners for fresh stem weight with leaves and pod characteristics.

Two crosses, $P_5 \times P_8$ (98.91) and $P_2 \times P_3$ (73.40) had highly significant positive SCA effects, whereas one cross, $P_4 \times P_6$ (61.71), had significant positive SCA effects, indicating that these hybrids had good specific combining ability for fresh stem weight without leaves and pod trait. Another 18 crossings had positive, but minor, SCA impacts and might be classified as average specific combiners. The remaining 15 crosses had negative SCA effects, with three ($P_1 \times P_5$, $P_2 \times P_9$, and $P_4 \times P_7$) having significant SCA values and so being classified as poor specific combiners for fresh stem weight without leaves and pod characteristic.

In kenaf, 18 cross pairings had positive SCA effects, while the other 18 had negative for the stick weight per plant, SCA impacts ranging from − 15.27 to 36.25. Hybrid $P_7 \times P_9$ had the largest significant positive SCA impact (36.25), followed by $P_1 \times P_4$ (28.89) and $P_5 \times P_8$ (27.97), implying that it was a good specific combiner for the trait of stick weight per plant. Three crosses ($P_1 \times P_9$, $P_2 \times P_9$ and $P_5 \times P_7$) having negatively significant SCA values, making them poor specific combiners for dry stick weight.

Two crosses, $P_2 \times P_3$ (11.24) and $P_5 \times P_8$ (7.47) showed highly significant positive SCA effects, while one cross, $P_2 \times P_5$ (3.60) showed significant positive SCA effects, implying better fiber yielding hybrids than their parents' mean and considered best specific combiners for increased fiber weight per plant of kenaf. The remaining 17 crosses, on the other hand, had positive SCA findings, but 16 had negative SCA outcomes. Crosses $P_1 \times P_5$ (− 5.28) and $P_2 \times P_9$ (− 10.37) were the worst specific combiners for the trait in question, with highly significant negative values.

The SCA effects on the number of pods per plant ranged from − 49.49 to 63.49. (Table 8). The cross combinations produced 21 positive SCA effects, with 11 of them having significant positive SCA values for the number

| Parents/Hybrids | PH | BD | CD | MD | TD | NN | DTFF | |
|---|---|---|---|---|---|---|---|---|
| P$_1$ | 247.41i–l | 25.74g–l | 21.77j–n | 12.17c–j | 4.31b–h | 6.91h–l | 52.00b–i | |
| P$_2$ | 230.44l | 21.45n–q | 17.89p–r | 9.69k | 4.47a–h | 4.15p | 54.17a–d | |
| P$_3$ | 276.91a–g | 24.70j–m | 21.10l–p | 12.49b–h | 4.06e–h | 4.80op | 48.33i–n | |
| P$_4$ | 280.59a–g | 25.47g–m | 21.88i–n | 12.29b–j | 4.31b–h | 5.10m–p | 52.67a–h | |
| P$_5$ | 265.45c–i | 24.61j–n | 20.99l–p | 12.23b–j | 4.36a–h | 7.38d–l | 49.17g–m | |
| P$_6$ | 255.22f–k | 20.88p–q | 17.15qr | 10.95g–k | 4.15c–h | 5.10n–p | 51.83b–j | |
| P$_7$ | 278.07a–g | 22.36m–q | 19.06n–r | 10.85h–k | 4.10d–h | 6.16l–o | 45.17m–o | |
| P$_8$ | 258.23d–k | 21.40o–q | 18.14o–r | 11.57d–j | 4.33b–h | 6.82i–m | 52.00b–i | |
| P$_9$ | 271.53a–i | 23.33k–p | 19.53m–r | 10.73i–k | 3.77g–h | 6.86h–l | 49.50g–l | |
| x̄ Parents | 262.65 | 23.33 | 19.72 | 11.44 | 4.21 | 5.92 | 50.54 | |
| P$_1$×P$_2$ | 252.56g–k | 26.28e–k | 22.35e–m | 11.22f–k | 3.66g–h | 7.17e–l | 52.67a–h | |
| P$_1$×P$_3$ | 272.47a–i | 29.22a–e | 25.32a–f | 12.65b–f | 4.87a–f | 9.23a–c | 50.17d–l | |
| P$_1$×P$_4$ | 264.25c–i | 29.07a–f | 25.09b–h | 12.77b–f | 4.06d–h | 8.48a–i | 50.00e–l | |
| P$_1$×P$_5$ | 234.13jl | 24.957i–m | 21.40k–n | 10.70i–k | 4.19b–h | 8.71a–f | 53.83a–e | |
| P$_1$×P$_6$ | 255.62e–k | 25.47g–m | 22.07g–n | 11.64d–j | 4.51a–h | 8.53a–i | 51.83b–j | |
| P$_1$×P$_7$ | 285.13a–d | 27.89c–i | 24.65c–j | 11.57d–j | 3.45h | 8.53a–i | 50.33c–l | |
| P$_1$×P$_8$ | 268.35b–i | 26.35e–k | 22.59d–m | 12.09c–j | 3.82f–h | 7.78b–l | 51.50b–k | |
| P$_1$×P$_9$ | 251.86g–k | 23.45k–p | 19.72m–r | 10.62jk | 4.12d–h | 6.35k–o | 53.67a–f | |
| P$_2$×P$_3$ | 244.52i–l | 31.68a | 28.43a | 12.58b–g | 4.72a–g | 9.36ab | 54.00a–e | |
| P$_2$×P$_4$ | 277.81a–g | 28.21b–h | 24.48c–k | 12.57b–g | 4.10d–h | 8.57a–h | 55.33ab | |
| P$_2$×P$_5$ | 252.45g–k | 26.88d–j | 23.73c–l | 11.35f–k | 3.46h–h | 8.98a–d | 56.33a | |
| P$_2$×P$_6$ | 260.21d–j | 25.79g–l | 22.13g–n | 11.17f–k | 3.78g–h | 8.01a–k | 51.33b–k | |
| P$_2$×P$_7$ | 269.95a–i | 25.86g–l | 22.02h–n | 11.09f–k | 3.68g–h | 6.88h–l | 46.33l–o | |
| P$_2$×P$_8$ | 259.92d–j | 24.48j–o | 20.89l–p | 11.51d–j | 4.39a–h | 7.47d–l | 50.00e–l | |
| P$_2$×P$_9$ | 219.58l | 19.95q | 16.83r | 9.74k | 4.26b–h | 4.89n–p | 52.67a–h | |
| P$_3$×P$_4$ | 291.87a–c | 29.25a–e | 25.41a–e | 13.09b–d | 4.14c–h | 8.67a–g | 50.67c–k | |
| P$_3$×P$_5$ | 285.98a–d | 26.11e–l | 22.62d–m | 12.28b–j | 4.24b–h | 6.99g–l | 48.67h–n | |
| P$_3$×P$_6$ | 284.5a–e | 25.99f–l | 22.20f–n | 12.24b–j | 4.05e–h | 7.24e–l | 49.33g–l | |
| P$_3$×P$_7$ | 297.85a | 24.56j–o | 20.78l–p | 12.14c–j | 4.36a–h | 6.56j–n | 45.00no | |
| P$_3$×P$_8$ | 280.28a–g | 27.01d–j | 22.69d–m | 12.31b–i | 4.22b–h | 8.87a–e | 50.67c–k | |
| P$_3$×P$_9$ | 270.78a–i | 24.11j–o | 20.67l–p | 11.37e–k | 4.60a–g | 6.45i–o | 50.67c–k | |
| P$_4$×P$_5$ | 272.93a–i | 29.16a–f | 24.95b–i | 13.88b | 4.49a–h | 7.99a–k | 48.67h–n | |
| P$_4$×P$_6$ | 272.75a–i | 30.28a–c | 26.48a–c | 12.69b–f | 4.15c–h | 8.35a–i | 47.50k–n | |
| P$_4$×P$_7$ | 281.6a–f | 25.54g–m | 21.68j–n | 12.73b–f | 5.27ab | 6.87h–l | 47.50k–n | |
| P$_4$×P$_8$ | 284.18a–e | 29.90a–d | 25.75a–d | 13.19b–d | 5.23a–c | 8.35a–i | 54.33a–c | |
| P$_4$×P$_9$ | 276.71a–h | 29.87a–d | 25.86a–c | 12.06c–j | 4.91a–e | 6.60j–n | 49.67f–l | |
| P$_5$×P$_6$ | 278.45a–g | 23.65k–p | 20.41m–p | 11.85d–j | 4.06e–h | 7.11f–l | 48.67h–n | |
| P$_5$×P$_7$ | 280.43a–g | 24.93i–m | 21.37k–n | 12.75b–f | 4.30b–h | 7.10f–l | 45.00no | |
| P$_5$×P$_8$ | 294.45ab | 31.15ab | 27.80ab | 15.74a | 5.15a–d | 8.13a–j | 51.50b–k | |
| P$_5$×P$_9$ | 248.78h–k | 23.03l–q | 19.82m–r | 11.56d–j | 3.77g–h | 7.63c–l | 47.83j–n | |
| P$_6$×P$_7$ | 271.49a–i | 24.85i–m | 21.62j–n | 12.33b–i | 5.44a | 7.18e–l | 47.67k–n | |
| P$_6$×P$_8$ | 263.88c–i | 25.21h–m | 21.37k–n | 10.82h–k | 4.53a–h | 6.91h–l | 52.83a–g | |
| P$_6$×P$_9$ | 260.09d–j | 26.13e–l | 22.40e–m | 11.89d–j | 4.91a–f | 9.68a | 48.50i–n | |
| P$_7$×P$_8$ | 286.03a–d | 23.45k–p | 20.08m–q | 11.28f–k | 4.09d–h | 6.09l–o | 45.17m–o | |
| P$_7$×P$_9$ | 296.17ab | 28.52a–g | 25.20b–g | 13.03b–e | 4.28b–h | 7.47d–l | 43.00o | |
| P$_8$×P$_9$ | 261.7d–j | 24.88i–m | 21.54j–n | 13.67b–c | 4.31b–h | 9.09a–d | 48.33i–n | |
| x̄ Hybrids | 269.71 | 26.47 | 22.84 | 12.11 | 4.32 | 7.73 | 50.03 | |
| Overall Mean | 268.30 | 25.85 | 22.22 | 11.98 | 4.30 | 7.37 | 50.13 | |
| Std Dev | 32.26 | 5.27 | 5.29 | 2.30 | 1.92 | 5.09 | 4.71 | |
| Std Error | 1.96 | 0.32 | 0.32 | 0.14 | 0.12 | 0.31 | 0.29 | |
| EMS | 644.08 | 7.80 | 7.73 | 2.18 | 0.92 | 2.28 | 12.34 | |
| LSD (5%) | 28.92 | 3.18 | 3.17 | 1.68 | 1.09 | 1.72 | 4.00 | |
| **Parents/hybrids** | **D50%F** | **FW1** | **FW2** | **DSW** | **DFW** | **NF** | **NS** | **SW** |
| P$_1$ | 60.67b–j | 1127.20k–r | 328.89e–l | 93.78g–o | 26.71e–i | 86.83o–t | 26.08b–f | 34.18ab |
| P$_2$ | 69.17a | 670.50tu | 225.00o | 74.56no | 17.56no | 50.82u | 20.08l–o | 33.78a–d |
| P$_3$ | 57.67c–m | 962.00n–t | 331.95d–k | 123.24a–h | 22.82h–m | 70.83s–u | 26.65a–e | 31.92g–m |
| Continued | | | | | | | | |

| Parents/hybrids | D50%F | FW1 | FW2 | DSW | DFW | NF | NS | SW |
|---|---|---|---|---|---|---|---|---|
| P₄ | 63.83a–e | 1118.00l–r | 351.42b–i | 90.62h–o | 24.78g–k | 67.56tu | 26.02b–f | 30.50n–s |
| P₅ | 58.00c–m | 818.10s–u | 247.97m–o | 79.60l–o | 19.49m–o | 92.84n–t | 28.76a | 30.33p–s |
| P₆ | 64.00a–d | 929.30o–t | 222.41o | 71.35o | 17.65no | 97.54m–s | 25.73b–g | 33.79a–d |
| P₇ | 55.67i–n | 937.80n–t | 258.77k–o | 96.27f–o | 16.30o | 121.94h–m | 20.59k–n | 32.65c–i |
| P₈ | 60.50b–j | 911.30p–t | 287.22h–o | 95.06g–o | 23.59h–m | 83.87p–t | 27.36ab | 33.04b–g |
| P₉ | 55.83i–n | 1102.30l–s | 255.87l–o | 81.46k–o | 19.17m–o | 106.78k–p | 27.79ab | 32.47d–j |
| x̄ Parents | 60.59 | 952.95 | 278.83 | 89.55 | 20.89 | 86.56 | 25.45 | 32.52 |
| P₁×P₂ | 59.83c–k | 1214.50f–o | 328.52e–l | 97.78f–o | 25.96f–i | 115.30i–o | 15.08s | 33.90a–c |
| P₁×P₃ | 59.83c–k | 1526.80a–d | 379.58a–f | 122.30a–i | 31.54b–d | 136.92d–j | 25.95b–f | 32.79c–i |
| P₁×P₄ | 57.50d–n | 1490.30b–g | 410.69a–c | 152.93a | 31.34b–e | 156.96b–f | 25.85b–f | 33.36b–f |
| P₁×P₅ | 61.50b–i | 1112.80l–r | 272.33j–o | 103.16d–n | 21.11j–n | 95.92m–t | 22.57h–k | 26.20x |
| P₁×P₆ | 61.00b–j | 1362.20c–l | 316.11e–m | 108.05c–n | 25.12g–k | 123.14g–m | 20.03m–o | 30.70m–r |
| P₁×P₇ | 56.83f–n | 1483.90b–h | 350.83b–i | 111.67c–m | 27.42c–h | 162.83b–d | 20.69k–n | 31.83g–o |
| P₁×P₈ | 58.83c–m | 1211.10f–o | 323.43e–l | 109.12c–m | 27.25d–h | 151.15b–g | 25.79b–g | 32.65c–i |
| P₁×P₉ | 62.83a–f | 1044.80m–s | 312.56e–m | 84.37j–o | 24.62g–k | 144.50b–h | 24.54e–h | 31.13j–q |
| P₂×P₃ | 61.33b–j | 1521.70a–e | 414.45a–c | 110.00c–m | 38.74a | 75.88q–u | 16.45q–s | 32.91b–h |
| P₂×P₄ | 64.17a–c | 1230.00e–n | 386.11a–e | 121.12a–i | 31.46b–e | 109.50j–p | 18.42o–q | 32.44d–j |
| P₂×P₅ | 66.50a | 1192.90h–p | 322.08e–m | 104.17c–n | 29.03b–g | 101.67m–r | 20.25l–o | 31.57h–p |
| P₂×P₆ | 59.00c–l | 1071.90l–s | 331.67e–k | 90.58h–o | 26.04f–i | 96.58m–s | 24.96c–g | 32.00f–m |
| P₂×P₇ | 52.33n | 1301.60d–m | 318.10e–m | 107.78c–n | 26.00f–i | 131.35e–l | 20.39l–o | 30.85l–q |
| P₂×P₈ | 59.33c–l | 1198.20g–p | 303.06g–n | 95.70g–o | 25.91f–j | 140.24d–i | 15.74rs | 35.05a |
| P₂×P₉ | 59.83c–k | 584.30u | 229.22no | 78.82mo | 18.94m–o | 83.91p–t | 17.81p–r | 33.67b–e |
| P₃×P₄ | 57.67c–m | 1573.90a–d | 415.19a–c | 133.33a–e | 29.93b–f | 98.61m–s | 25.67b–g | 29.40r–u |
| P₃×P₅ | 59.50c–l | 1478.80b–hh | 383.71a–e | 130.00a–f | 25.89f–j | 123.69g–m | 26.56b–e | 31.49i–p |
| P₃×P₆ | 59.00c–l | 1101.90l–s | 305.56f–m | 114.54b–k | 22.86h–m | 136.07d–j | 24.18f–i | 30.98k–q |
| P₃×P₇ | 51.00n | 1137.00k–r | 353.02b–h | 126.30a–g | 24.88g–k | 105.17l–p | 20.95k–n | 31.69g–p |
| P₃×P₈ | 58.17c–m | 1413.90b–k | 343.33c–j | 130.00a–f | 24.78g–k | 134.39d–k | 23.68g–j | 28.35u–v |
| P₃×P₉ | 58.33c–m | 887.90q–t | 290.00h–o | 105.31c–n | 22.29i–n | 106.08k–p | 26.72a–d | 29.90q–t |
| P₄×P₅ | 59.33c–l | 1660.40ab | 367.50b–g | 116.79b–j | 28.76b–g | 120.28h–n | 26.68a–e | 28.72t–v |
| P₄×P₆ | 55.67i–n | 1786.50a | 419.35ab | 134.46a–d | 28.87b–g | 172.30b | 24.98c–g | 32.11f–l |
| P₄×P₇ | 58.67c–m | 1174.30i–q | 303.52g–n | 112.92c–l | 23.47h–m | 75.45r–u | 19.26n–p | 27.55v–x |
| P₄×P₈ | 60.50b–j | 1360.70c–l | 403.78a–d | 134.09a–d | 29.05b–g | 96.00m–t | 26.86a–c | 29.78q–t |
| P₄×P₉ | 56.33f–n | 1627.00a–c | 449.96a | 147.69a | 32.11bc | 100.78m–r | 27.30ab | 32.31e–k |
| P₅×P₆ | 57.67c–m | 850.90r–u | 266.85k–o | 95.37g–o | 22.29i–n | 104.46l–q | 26.47b–e | 29.18s–u |
| P₅×P₇ | 53.17ln | 1209.40f–o | 329.35e–l | 92.22h–o | 19.73l–o | 160.25b–e | 26.78a–d | 30.72m–r |
| P₅×P₈ | 56.17 g–n | 1655.30ab | 419.49ab | 137.78a–c | 32.81b | 134.25d–k | 22.22i–l | 26.95wx |
| P₅×P₉ | 56.00 h–n | 1206.70g–o | 277.08i–o | 103.78d–n | 25.14f–k | 130.72f–l | 24.67d–h | 30.43p–s |
| P₆×P₇ | 57.33e–n | 1088.90l–s | 270.83j–o | 88.89i–o | 20.36k–o | 144.31b–h | 22.63h–k | 31.87g–n |
| P₆×P₈ | 62.67a–g | 1435.10b–j | 294.83g–o | 90.72h–o | 22.16i–n | 158.92b–f | 26.28b–f | 31.82g–o |
| P₆×P₉ | 62.50b–h | 1463.20b–i | 305.50f–m | 100.12e–n | 24.51g–l | 170.63bc | 25.70b–g | 30.46o–s |
| P₇ₓP₈ | 53.33 k–n | 1149.60j–q | 313.34e–m | 109.30c–m | 22.05i–n | 113.99i–o | 19.18n–p | 28.03u–w |
| P₇×P₉ | 51.00n | 1652.40a–c | 348.28b–i | 132.68a–e | 25.56f–j | 217.15a | 21.82j–m | 30.07q–t |
| P₈×P₉ | 54.83j–n | 1501.90a–f | 296.76g–o | 115.65b–j | 25.03g–k | 142.45c–i | 27.27ab | 30.33p–s |
| x̄ Hybrids | 58.32 | 1304.52 | 337.67 | 112.49 | 26.19 | 126.99 | 23.07 | 30.92 |
| OA Mean | 58.77 | 1234.20 | 325.90 | 107.90 | 25.13 | 118.91 | 23.54 | 31.24 |
| Std Dev | 7.38 | 518.40 | 100.62 | 39.78 | 8.44 | 52.10 | 5.53 | 4.23 |
| Std Error | 0.45 | 31.55 | 6.12 | 2.42 | 0.51 | 3.17 | 0.34 | 0.26 |
| EMS | 33.12 | 65,920.85 | 4361.17 | 877.24 | 17.80 | 646.90 | 3.60 | 1.46 |
| LSD5% | 6.56 | 292.55 | 75.25 | 33.75 | 4.81 | 28.98 | 2.16 | 1.38 |

**Table 6.** Mean performance of nine parents and their hybrids for 15 yield and yield contributing characters in kenaf. *PH* plant height (cm), *BD* base diameter (mm), *CD* core diameter (mm), *MD* middle diameter (mm), *TD* top diameter (mm), *NN* number of nodes, *DTFF* days to 1st flowering, *Std Dev* standard deviation, *EMS* error means square, *LSD* Least significant difference, *D50%F* Days to 50% flowering, *FW1* fresh stem weight with leaves and pod (g), *FW2* fresh stem weight without leaves and pod (g), *DSW* dry stick weight (g), *DFW* dry fiber weight (g), *NF* number of pods per plant, *NS* number of seeds per pod, *SW* 1000 seeds weight (g), *OA mean* overall mean. Means with the same letter in each letter in each column are not significantly different at 5% probability level.

| Traits | P₁ | P₂ | P₃ | P₄ | P₅ | P₆ | P₇ | P₈ | P₉ | LSD (gi–gj) 5% | 1% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| PH | − 10.34** | − 17.73** | 8.11* | 8.22** | − 1.31 | − 3.22 | 11.99** | 2.03 | 2.24 | 4.11 | 5.43 |
| BD | 0.68 | − 0.43 | 0.96** | 2.32** | 0.22 | − 0.69* | − 0.58 | − 0.14 | − 2.34* | 0.45 | 0.60 |
| CD | 0.60 | − 0.32 | 0.92** | 2.12** | 0.36 | − 0.65 | − 0.42 | − 0.11 | − 2.49* | 0.45 | 0.59 |
| MD | − 0.11 | − 0.74** | 0.44* | 0.80** | 0.53** | − 0.21 | − 0.01 | 0.45* | − 1.15* | 0.24 | 0.32 |
| TD | − 0.10 | − 0.13 | 0.09 | 0.24* | .00 | 0.12 | 0.06 | 0.18 | − 0.46 | 0.16 | 0.20 |
| NN | 0.49** | − 0.33 | − 0.03 | 0.07 | 0.38* | − 0.01 | − 0.39* | 0.28 | − 0.47 | 0.24 | 0.32 |
| DTFF | 1.50** | 2.32** | − 0.51 | 0.69 | − 0.24 | − 0.01 | − 3.74** | 0.63 | − 0.64 | 0.57 | 0.75 |
| D50%F | 1.25 | 3.17** | − 0.51 | 1.07 | 0.01 | 1.55* | − 3.71** | − 0.09 | − 2.74 | 0.93 | 1.23 |
| FW1 | 45.42 | − 140.47** | 33.15 | 176.17** | − 17.97 | − 16.56 | − 11.68 | 49.76 | − 117.80 | 41.59 | 54.89 |
| FW2 | 13.76 | − 10.66 | 31.66** | 59.86** | − 6.01 | − 22.27** | − 8.70 | 6.54 | − 64.18** | 10.70 | 14.12 |
| DSW | 2.24 | − 8.84* | 15.09** | 16.57** | − 0.89 | − 7.89* | 2.00 | 5.47 | − 23.76** | 4.80 | 6.33 |
| DFW | 2.00** | 1.04* | 1.89** | 3.53** | − 0.19 | − 1.66** | − 2.15** | 0.95 | − 5.41** | 0.68 | 0.90 |
| NF | 9.02** | − 18.64** | − 9.33** | − 8.74** | − 0.38 | 12.76** | 17.57** | 7.09* | − 9.34 | 4.12 | 5.44 |
| NS | − 0.56* | − 4.50** | 0.42 | 0.75** | 1.36** | 0.72** | − 2.36** | 0.27 | 3.91** | 0.31 | 0.41 |
| SW | 0.65** | 1.47** | − 0.22 | − 0.65** | − 1.63** | 0.26 | − 0.54** | − 0.43** | 1.09* | 0.20 | 0.26 |

**Table 7.** Estimates of general combining ability effect (GCA) for 15 morphological characters of kenaf. *LSD* least significant difference, *PH* plant height, *BD* base diameter, *CD* core diameter, *MD* middle diameter, *TD* top diameter, *NN* number of nodes, *DTFF* days to 1st flowering, *D50%F* days to 50% flowering, *FW1* fresh stem weight with leaves and pod, *FW2* fresh stem weight without leaves and pod, *DSW* dry stick weight, *DFW* dry fiber weight, *NF* number of pods per plant, *NS* number of seeds per pod, *SW* 1000 seeds weight. **Highly significant at P ≤ 0.01 level, *Significant at P ≤ 0.05 level.

of pods per plant. The crosses $P_2 \times P_3$ (7.20), $P_3 \times P_4$ (4.70), and $P_2 \times P_4$ (3.32) had highly significant positive SCA effects, but $P_4 \times P_6$ (− 3.43), $P_1 \times P_3$ (− 2.18), and $P_1 \times P_5$ (− 1.05) had highly significant negative SCA effects.

SCA impacts ranged from − 4.01 to 4.87 for the quantity of seeds per pod (Table 8). Sixteen of the cross combinations had positive SCA effects, with six ($P_1 \times P_3$, $P_1 \times P_8$, $P_2 \times P_6$, $P_2 \times P_7$, $P_4 \times P_8$ and $P_5 \times P_7$) having highly significant positive SCA values and two ($P_1 \times P_4$ and $P_6 \times P_8$) having significant positive SCA values considered as good specific combiners for the number of seeds per pod characteristic. The remaining 20 crosses had negative SCA effects, with 12 of them having highly significant negative SCA effects and were considered the poorest specific combiners for the trait under consideration.

For the character 1000 seeds weight, the SCA effects ranged from − 4.20 to 2.64 (Table 8). Hybrids $P_1 \times P_5$, $P_1 \times P_6$, $P_2 \times P_7$, $P_3 \times P_8$, $P_4 \times P_7$, $P_5 \times P_8$, and $P_7 \times P_8$, all exhibited highly significant negative SCA effects, whilst $P_3 \times P_9$, $P_3 \times P_4$, and $P_2 \times P_6$ had significant negative SCA effects, indicating that these hybrids had good specific combining capacity for smaller seed size. Seven more crossings exhibited negative but minor SCA effects, indicating that they are average specific combiners. The remaining 19 crosses had positive SCA effects, with five having highly significant SCA values and three having significant SCA values that were considered poor specific combiners for the 1000 seed weight trait.

### Estimation of heterosis effect of kenaf hybrids for yield and yield components and morphological traits.
Heterosis was calculated using the relative performance of hybrids with mid-parent (MPH) and better-parent (BPH) values. Parent heterosis is favored over mid-parent heterosis in hybrid formation. High positive heterosis values are preferable for yield production traits, whereas negative values are favored for node number and 1000 seed weight.

### Relative heterosis response in pooled environments.
Percentage heterosis relative to mid-parents (MPs) was significantly positive in 13 out of 36 crosses for dry fiber weight (25.74–91.94), five crosses for dry stick weight (49.3–71.65), and 20 crosses for number of pods per plant (49.22–108.72). However, mid-parents of 18 crosses for fresh stem weight with leaves and pod (32.75–91.43) and five crosses for fresh stem weights without leaves and pod (46.16–56.76) were significantly positive (Table 9). For 1000 seed weight, 29 crosses out of 36 had negative heterosis (in the desired direction). This indicates that they had smaller-sized seeds. Over dominance was observed in cross $P_5 \times P_8$ for base diameter, core diameter, middle diameter, fresh stem weight with leaves and pods, and fresh stem weight without leaves and pods, as well as cross $P_4 \times P_6$ for base diameter, core diameter, fresh stem weight with leaves and pods, fresh stem weight without leaves and pods, and pods number per plant and the cross $P_2 \times P_3$ for base diameter and core diameter, with a high potency's ratio. Furthermore, the crosses $P_2 \times P_3$ and $P_2 \times P_5$ for fiber yield, and the crosses $P_1 \times P_4$ and $P_4 \times P_9$ for stick yield features had the highest mid parent heterosis. Due to the existence of over dominance, crosses $P_1 \times P_4$, $P_2 \times P_8$ and $P_7 \times P_9$ were chosen for pods number per plant for seed yield. Negative heterosis estimates for the nodes number and 1000 seed weight are desirable, where small values for these traits indicate good fiber quality and smaller seed size, therefore, negative magnitude implies high heterosis. Cross $P_2 \times P_9$ had the lowest negative nodes number value (− 11.02)

| Hybrids | PH | BD | CD | MD | TD | NN | DTFF | D50%F | FW1 | FW2 | DSW | DFW | NF | NS | SW |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $P_1 \times P_2$ | 11.33 | 0.36 | 0.06 | 0.20 | − 0.35 | − 0.31 | − 1.31 | − 3.16 | 89.44 | 5.37 | − 0.85 | − 1.66 | 8.80 | − 3.73** | 0.40 |
| $P_1 \times P_3$ | 5.4 | 1.91 | 1.78 | 0.44 | 0.64 | 1.45* | − 0.97 | 0.52 | 228.07* | 14.12 | − 0.26 | 3.07 | 21.11* | 2.20** | 0.98* |
| $P_1 \times P_4$ | − 2.92 | 0.40 | 0.36 | 0.20 | − 0.32 | 0.59 | − 2.34 | − 3.39 | 48.58 | 17.03 | 28.89* | 1.23 | 40.57** | 1.78* | 1.98** |
| $P_1 \times P_5$ | − 23.51* | − 1.61 | − 1.57 | − 1.60** | 0.05 | 0.52 | 2.42 | 1.67 | − 134.78 | − 55.46* | − 3.42 | − 5.28** | − 28.84** | − 2.11** | − 4.20** |
| $P_1 \times P_6$ | − 0.11 | − 0.19 | 0.11 | 0.08 | 0.24 | 0.73 | 0.19 | − 0.38 | 113.25 | 4.57 | 8.48 | 0.20 | − 14.76 | − 4.01** | − 1.59** |
| $P_1 \times P_7$ | 14.19 | 2.12* | 2.46* | − 0.19 | − 0.75* | 1.11 | 2.42 | 0.71 | 230.03* | 25.72 | 2.20 | 2.99 | 20.13* | − 0.28 | 0.34 |
| $P_1 \times P_8$ | 7.36 | 0.14 | 0.09 | − 0.14 | − 0.51 | − 0.31 | − 0.78 | − 0.91 | − 104.18 | − 16.92 | − 3.82 | − 0.28 | 18.92* | 2.20** | 1.06* |
| $P_1 \times P_9$ | − 10.54 | − 1.84 | − 1.84 | 0.50 | 0.72 | − 2.38** | 1.51 | 5.34 | − 286.68 | 24.25 | − 15.27 | 1.58 | − 18.62 | 0.63 | − 0.48 |
| $P_2 \times P_3$ | − 15.15 | 5.47** | 5.81** | 1.00 | 0.52 | 2.39** | 2.04 | 0.09 | 408.87** | 73.40** | − 1.48 | 11.24** | − 12.26 | − 3.35** | 0.29 |
| $P_2 \times P_4$ | 18.03 | 0.65 | 0.67 | 0.64 | − 0.25 | 1.50** | 2.18 | 1.35 | − 25.82 | 16.87 | 8.16 | 2.32 | 20.77* | − 1.71* | 0.24 |
| $P_2 \times P_5$ | 2.20 | 1.42 | 1.68 | − 0.32 | − 0.66 | 1.60** | 4.10** | 4.74* | 131.24 | 18.71 | 8.67 | 3.60* | 4.58 | − 0.49 | 0.35 |
| $P_2 \times P_6$ | 11.87 | 1.23 | 1.09 | 0.24 | − 0.46 | 1.02 | − 1.12 | − 4.30* | 8.79 | 44.55 | 2.09 | 2.08 | − 13.65 | 4.87** | − 1.11* |
| $P_2 \times P_7$ | 6.40 | 1.20 | 0.75 | − 0.03 | − 0.49 | 0.27 | − 2.40 | − 5.71** | 233.61* | 17.41 | 9.39 | 2.54 | 16.32 | 3.37** | − 1.46** |
| $P_2 \times P_8$ | 6.33 | − 0.63 | − 0.70 | − 0.07 | 0.10 | 0.19 | − 3.09* | − 2.33 | 68.77 | − 12.87 | − 6.17 | − 0.66 | 35.68** | − 3.91** | 2.64** |
| $P_2 \times P_9$ | − 37.62** | − 6.33** | − 5.86** | − 0.95 | 1.10* | − 4.15** | 0.22 | 5.07 | − 646.22** | − 89.71* | − 6.81 | − 10.37** | − 32.23* | − 0.26 | − 0.81 |
| $P_3 \times P_4$ | 6.26 | 0.30 | 0.36 | − 0.03 | − 0.42 | 1.30* | 0.35 | − 1.47 | 144.45 | 3.62 | − 3.56 | − 0.07 | 0.57 | 0.61 | − 1.11* |
| $P_3 \times P_5$ | 9.89 | − 0.74 | − 0.67 | − 0.57 | − 0.08 | − 0.68 | − 0.73 | 1.43 | 243.52* | 38.01 | 10.57 | − 0.39 | 17.30 | 0.90 | 1.96** |
| $P_3 \times P_6$ | 10.33 | 0.04 | − 0.09 | 0.12 | − 0.39 | − 0.06 | − 0.29 | − 0.62 | − 134.86 | − 23.88 | 2.12 | − 1.95 | 16.53 | − 0.84 | − 0.44 |
| $P_3 \times P_7$ | 8.46 | − 1.49 | − 1.73 | − 0.17 | − 0.03 | − 0.35 | − 0.90 | − 3.36 | − 104.58 | 10.01 | 3.98 | 0.57 | − 19.18 | − 0.99 | 1.07* |
| $P_3 \times P_8$ | 0.85 | 0.51 | − 0.14 | − 0.46 | − 0.28 | 1.29* | 0.41 | 0.18 | 110.86 | − 14.92 | 4.21 | − 2.64 | 20.52* | − 0.89 | − 2.37** |
| $P_3 \times P_9$ | − 17.46 | − 3.08* | − 2.54 | − 0.07 | 0.39 | − 2.86** | 0.89 | 3.12 | − 571.94** | − 48.94 | − 3.41 | − 4.30 | − 17.98 | 0.43 | − 1.36* |
| $P_4 \times P_5$ | − 3.27 | 0.96 | 0.46 | 0.68 | 0.02 | 0.22 | − 1.93 | − 0.32 | 282.07** | − 6.40 | − 4.12 | 0.84 | 13.29 | 0.70 | − 0.39 |
| $P_4 \times P_6$ | − 1.54 | 2.98** | 3.00** | 0.22 | − 0.45 | 0.95 | − 3.32* | − 5.53* | 406.76** | 61.71* | 20.56 | 2.43 | 52.16** | − 0.37 | 1.11* |
| $P_4 \times P_7$ | − 7.90 | − 1.87 | − 2.03 | 0.07 | 0.73* | − 0.15 | 0.41 | 2.73 | − 210.35* | − 67.69** | − 10.88 | − 2.48 | − 49.49** | − 3.01** | − 2.64** |
| $P_4 \times P_8$ | 4.64 | 2.05 | 1.73 | 0.07 | 0.57 | 0.67 | 2.88* | 0.94 | − 85.37 | 17.33 | 6.81 | .00 | − 18.46 | 1.96** | − 0.52 |
| $P_4 \times P_9$ | − 8.17 | − 0.62 | − 0.16 | − 0.65 | 0.50 | − 2.71** | 0.63 | 2.56 | − 105.89 | 45.89 | 1.89 | 2.57 | − 28.33* | − 0.60 | 0.91 |
| $P_5 \times P_6$ | 13.69 | − 1.55 | − 1.31 | − 0.35 | − 0.30 | − 0.59 | − 1.23 | − 2.47 | − 334.72** | − 24.91 | − 1.07 | − 0.44 | − 24.03* | 0.52 | − 0.84 |
| $P_5 \times P_7$ | 0.46 | − 0.38 | − 0.58 | 0.36** | .00 | − 0.22 | − 1.17 | − 1.71 | 18.98 | 24.01 | − 14.12 | − 2.51 | 26.95** | 3.90** | 1.50** |
| $P_5 \times P_8$ | 24.44* | 5.40** | 5.53** | 2.88 | 0.73* | 0.15 | 0.97 | − 2.33 | 403.43** | 98.91** | 27.97* | 7.47** | 11.43 | − 3.28** | − 2.37** |
| $P_5 \times P_9$ | − 22.66 | − 2.01 | − 1.80 | − 0.39 | 0.12 | − 0.30 | − 1.93 | − 0.43 | − 243.69 | − 32.82 | − 0.65 | 1.43 | 1.82 | − 2.31* | 1.79** |
| $P_6 \times P_7$ | − 6.57 | 0.45 | 0.68 | 0.67 | 1.01** | 0.24 | 1.27 | 0.91 | − 102.99 | − 18.25 | − 10.45 | − 0.41 | − 2.13 | 0.39 | 0.76 |
| $P_6 \times P_8$ | − 4.22 | 0.36 | 0.12 | − 1.31* | − 0.01 | − 0.69 | 2.07 | 2.62 | 181.83 | − 9.49 | − 12.09 | − 1.70 | 22.96* | 1.42* | 0.61 |
| $P_6 \times P_9$ | − 15.84 | 0.08 | − 0.04 | 0.85 | 0.68 | 0.61 | 0.72 | 7.44* | 119.67 | 18.80 | 8.46 | 3.39 | 7.00 | − 2.39* | − 0.39 |
| $P_7 \times P_8$ | 2.72 | − 1.51 | − 1.41 | − 1.04 | − 0.40 | − 1.13* | − 1.87 | − 1.45 | − 108.55 | − 4.56 | − 3.40 | − 1.32 | − 26.78** | − 2.61** | − 2.38** |
| $P_7 \times P_9$ | − 2.56 | 3.62* | 3.98* | 1.32 | 0.18 | 0.62 | − 0.27 | 3.38 | 302.83* | 57.22 | 36.25* | 4.57 | 63.49** | − 2.19* | 0.47 |
| $P_8 \times P_9$ | − 27.00 | − 2.32 | − 1.55 | 1.28 | 0.08 | 0.89 | − 1.19 | 1.18 | − 58.46 | − 11.56 | 7.59 | 2.02 | − 17.84 | 2.17 | 0.82 |
| LSD (sij-slk)5% | 18.70 | 2.06 | 2.05 | 1.09 | 0.71 | 1.11 | 2.59 | 4.24 | 189.23 | 48.7 | 21.83 | 3.11 | 18.75 | 1.40 | 0.89 |
| LSD (sij-slk)1% | 24.68 | 2.72 | 2.70 | 1.44 | 0.93 | 1.47 | 3.42 | 5.60 | 249.71 | 64.2 | 28.81 | 4.10 | 24.74 | 1.84 | 1.18 |
| LSD (sij-skl)5% | 16.55 | 1.82 | 1.81 | 0.96 | 0.62 | 0.98 | 2.29 | 3.75 | 167.40 | 43.1 | 19.31 | 2.75 | 16.58 | 1.24 | 0.79 |
| LSD (sij-skl)1% | 21.84 | 2.40 | 2.39 | 1.27 | 0.82 | 1.30 | 3.02 | 4.95 | 220.91 | 56.8 | 25.48 | 3.63 | 21.88 | 1.63 | 1.04 |

**Table 8.** Estimates of specific combining ability (SCA) effects for 15 different morphological characters of kenaf. *LSD* least significant difference, *PH* plant height, *BD* base diameter, *CD* core diameter, *MD* middle diameter, *TD* top diameter, *NN* number of nodes, *DTFF* days to 1st flowering, *D50%F* days to 50% flowering, *FW1* fresh stem weight with leaves and pod, *FW2* fresh stem weight without leaves and pod, *DSW* dry stick weight, *DFW* dry fiber weight, *NF* number of pods per plant, *NS* number of seeds per pod, *SW* 1000 seeds weight. *Significant at P ≤ 0.05 level, **Highly significant at P ≤ 0.01 level.

| Hybrids | PH MPH | PH BPH | BD MPH | BD BPH | CD MPH | CD BPH | MD MPH | MD BPH | TD MPH | TD BPH | NN MPH | NN BPH | DTFF MPH | DTFF BPH | D50%F MPH | D50%F BPH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| P₁×P₂ | 5.71 | 2.08 | 11.39 | 2.09 | 12.70 | 2.66 | 2.67 | − 7.80 | − 16.57 | − 18.04 | 29.70 | 3.74 | − 0.78 | 1.28 | − 7.83 | -13.49 |
| P₁×P₃ | 3.93 | − 1.61 | 15.87* | 13.51* | 18.12 | 16.30 | 2.62 | 1.32 | 16.36 | 12.90 | 57.74** | 33.59 | .00 | − 3.53 | 1.13 | -1.37 |
| P₁×P₄ | 0.09 | − 5.82 | 13.51 | 12.91 | 14.96 | 14.66 | 4.37 | 3.87 | − 5.79 | − 5.86 | 41.09* | 22.63 | − 4.46 | − 5.06 | − 7.63 | -9.92 |
| P₁×P₅ | − 8.70 | − 11.80 | − 0.87 | − 3.05 | 0.11 | − 1.68 | − 12.34 | − 12.56 | − 3.33 | − 3.83 | 21.95 | 18.12 | 6.43 | 3.53 | 3.65 | 1.37 |
| P₁×P₆ | 1.71 | 0.16 | 9.26 | − 1.06 | 13.44 | 1.40 | 0.69 | − 4.35 | 6.47 | 4.48 | 42.14* | 23.46 | − 0.16 | − 0.32 | − 2.14 | -4.69 |
| P₁×P₇ | 8.52 | 2.54 | 15.98 | 8.35 | 20.75* | 13.24* | 0.49 | − 4.96 | − 18.07 | − 20.06 | 30.53 | 23.46 | 3.60 | − 3.21 | − 2.29 | -6.32 |
| P₁×P₈ | 6.14 | 3.92 | 11.80 | 2.36 | 13.22 | 3.79 | 1.81 | − 0.70 | − 11.63 | − 11.79 | 13.28 | 12.54 | − 0.96 | − 0.96 | − 2.89 | -3.02 |
| P₁×P₉ | − 2.94 | − 7.25 | − 4.42 | − 8.90 | − 4.49 | − 9.40 | − 7.28 | − 12.78 | 1.94 | − 4.45 | − 7.82 | − 8.20 | 5.75 | 3.21 | 7.87 | 3.57 |
| P₂×P₃ | − 3.61 | − 11.70 | 37.32** | 28.28** | 45.81** | 34.73** | 13.45 | 0.73 | 10.74 | 5.60 | 109.27** | 95.10** | 5.37 | − 0.31 | − 3.29 | -11.33 |
| P₂×P₄ | 8.72 | − 0.99 | 20.25* | 10.75* | 23.12* | 11.89* | 14.40 | 2.30 | − 6.62 | − 8.34 | 85.24** | 67.85** | 3.59 | 2.15 | − 3.51 | -7.23 |
| P₂×P₅ | 1.82 | − 4.90 | 16.75 | 9.24 | 22.09* | 13.08* | 3.51 | − 7.26 | − 21.71 | − 22.70 | 55.81** | 21.69 | 9.03 | 4.00 | 4.59 | -3.86 |
| P₂×P₆ | 7.15 | 1.95 | 21.85* | 20.26* | 26.30* | 23.68* | 8.19 | 1.95 | − 12.38 | − 15.50 | 73.40** | 57.25* | − 3.14 | − 5.23 | − 11.39 | -14.70 |
| P₂×P₇ | 6.17 | − 2.92 | 18.10 | 15.69 | 19.18 | 15.53 | 7.98 | 2.19 | − 14.09 | − 17.63 | 33.42 | 11.58 | − 6.71 | − 14.46 | − 16.15 | -24.34 |
| P₂×P₈ | 6.38 | 0.66 | 14.29 | 14.16 | 15.93 | 15.13 | 8.32 | − 0.49 | − 0.16 | − 1.76 | 36.18 | 9.47 | − 5.81 | − 7.69 | − 8.48 | -14.22 |
| P₂×P₉ | − 12.51 | − 19.13 | − 10.90 | − 14.50 | − 10.05 | − 13.82 | − 4.58 | − 9.21 | 3.38 | − 4.69 | − 11.02 | − 28.61 | 1.61 | − 2.77 | − 4.27 | -13.49 |
| P₃×P₄ | 4.71 | 4.71 | 16.61* | 16.61* | 18.26 | 18.26 | 5.67 | 5.67 | − 0.97 | − 0.97 | 75.25** | 75.25** | 0.33 | 0.33 | − 5.08 | -5.08 |
| P₃×P₅ | 5.46 | 3.27 | 5.92 | 5.74 | 7.50 | 7.22 | − 0.65 | − 1.67 | 0.77 | − 2.72 | 14.87 | − 5.22 | − 0.17 | − 1.02 | 2.88 | 2.59 |
| P₃×P₆ | 6.93 | 2.74 | 14.04 | 5.24 | 16.07 | 5.20 | 4.40 | − 2.03 | − 1.29 | − 2.44 | 46.34* | 42.03 | − 1.50 | − 4.82 | − 3.01 | -7.81 |
| P₃×P₇ | 7.34 | 7.11 | 4.41 | − 0.54 | 3.51 | − 1.50 | 4.01 | − 2.80 | 6.84 | 6.23 | 19.76 | 6.47 | − 3.74 | − 6.90 | − 10.00 | -11.56 |
| P₃×P₈ | 4.75 | 1.22 | 17.19 | 9.36 | 15.64 | 7.54 | 2.32 | − 1.44 | 0.74 | − 2.43 | 52.65** | 29.98 | 1.00 | − 2.56 | − 1.55 | -3.86 |
| P₃×P₉ | − 1.26 | − 2.22 | 0.42 | − 2.36 | 1.75 | − 2.03 | − 2.04 | − 8.94 | 17.55 | 13.44 | 10.73 | − 5.91 | 3.58 | 2.36 | 2.79 | 1.16 |
| P₄×P₅ | − 0.03 | − 2.73 | 16.46* | 14.50* | 16.41 | 14.03 | 13.20 | 12.94 | 3.75 | 3.13 | 28.09 | 8.37 | − 4.42 | − 7.59 | − 2.60 | -7.05 |
| P₄×P₆ | 1.81 | − 2.79 | 30.64** | 18.88** | 35.71** | 21.02** | 9.21 | 3.26 | − 1.94 | − 3.69 | 63.65** | 63.50* | − 9.09 | − 9.81 | − 12.91 | -13.02 |
| P₄×P₇ | 0.81 | 0.36 | 6.80 | 0.27 | 5.90 | − 0.93 | 9.99 | 3.56 | 25.34 | 22.38 | 21.89 | 11.42 | − 2.90 | − 9.81 | − 1.81 | -8.09 |
| P₄×P₈ | 5.49 | 1.28 | 27.60** | 17.40** | 28.69** | 17.70** | 10.59 | 7.36 | 21.08 | 20.78 | 40.04* | 22.40 | 3.82 | 3.16 | − 2.68 | -5.22 |
| P₄×P₉ | 0.24 | − 1.38 | 22.40** | 17.26** | 24.89** | 18.18* | 4.76 | − 1.89 | 21.65 | 14.12 | 10.29 | − 3.79 | − 2.77 | − 5.70 | − 5.85 | -11.75 |
| P₅×P₆ | 6.96 | 4.90 | 3.97 | − 3.91 | 7.05 | − 2.75 | 2.24 | − 3.12 | − 4.66 | − 6.92 | 14.03 | − 3.59 | − 3.63 | − 6.11 | − 5.46 | -9.90 |
| P₅×P₇ | 3.19 | 0.85 | 6.14 | 1.28 | 6.74 | 1.83 | 10.42 | 4.19 | 1.55 | − 1.42 | 4.82 | − 3.80 | − 4.59 | − 8.47 | − 6.45 | -8.33 |
| P₅×P₈ | 12.46 | 10.92 | 35.43** | 26.59** | 42.06** | 32.43** | 32.25** | 28.67** | 18.55 | 18.14 | 14.58 | 10.28 | 1.81 | − 0.96 | − 5.20 | -7.16 |
| P₅×P₉ | − 7.34 | − 8.38 | − 3.91 | − 6.41 | − 2.16 | − 5.56 | 0.68 | − 5.50 | − 7.32 | − 13.54 | 7.23 | 3.45 | − 3.04 | − 3.37 | − 1.61 | -3.45 |
| P₆×P₇ | 1.82 | − 2.37 | 14.96 | 11.18 | 19.42 | 13.43 | 13.07 | 12.56 | 31.71 | 30.93 | 27.51 | 16.46 | − 1.72 | − 8.04 | − 4.18 | -10.42 |
| P₆×P₈ | 2.79 | 2.19 | 19.25* | 17.82* | 21.13 | 17.80 | − 3.95 | − 6.52 | 6.92 | 4.75 | 15.89 | 1.22 | 1.77 | 1.60 | 0.67 | -2.08 |
| P₆×P₉ | − 1.25 | − 4.21 | 18.21* | 12.01* | 22.15* | 14.69* | 9.64 | 8.53 | 23.82 | 18.16 | 62.02** | 41.22* | − 4.28 | − 6.43 | 4.31 | -2.34 |
| P₇ₓP₈ | 6.67 | 2.86 | 7.18 | 4.88 | 7.94 | 5.35 | 0.59 | − 2.53 | − 3.01 | − 5.53 | − 6.20 | − 10.73 | − 7.03 | − 13.14 | − 8.18 | -11.85 |
| P₇×P₉ | 7.78 | 6.51 | 24.86** | 22.25** | 30.62** | 29.04** | 20.77* | 20.08 | 8.65 | 4.28 | 14.82 | 9.02 | − 9.15 | − 13.13 | − 8.52 | -8.66 |
| P₈×P₉ | − 1.20 | − 3.62 | 11.24 | 6.64 | 14.33 | 10.27 | 22.60* | 18.13 | 6.39 | − 0.44 | 32.91* | 32.59 | − 4.76 | − 7.05 | − 5.73 | -9.37 |
| Mean | 2.69 | − 0.93 | 13.61 | 8.47 | 15.97 | 10.07 | 5.95 | 1.13 | 2.91 | 0.13 | 32.84 | 19.56 | − 1.03 | − 3.80 | − 3.69 | -7.40 |
| LSD5% | 35.42 | 40.90 | 3.90 | 4.50 | 3.88 | 4.48 | 2.06 | 2.38 | 1.34 | 1.55 | 2.11 | 2.43 | 4.90 | 5.66 | 8.03 | 9.28 |
| LSD1% | 46.75 | 53.98 | 5.14 | 5.94 | 5.12 | 5.91 | 2.72 | 3.14 | 1.77 | 2.04 | 2.78 | 3.21 | 6.47 | 7.47 | 10.60 | 12.24 |

| Hybrids | FW1 MPH | FW1 BPH | FW2 MPH | FW2 BPH | DSW MPH | DSW BPH | DFW MPH | DFW BPH | NF MPH | NF BPH | NS MPH | NS BPH | SW MPH | SW BPH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| P₁×P₂ | 35.12 | 7.74 | 18.62 | − 0.11 | 16.17 | 4.26 | 17.29 | − 2.81 | 67.52* | 32.78 | − 34.66 | − 42.18 | − 0.24 | − 0.82 |
| P₁×P₃ | 46.15* | 35.44* | 14.88 | 14.35 | 12.71 | − 0.76 | 27.35* | 18.06 | 73.68** | 57.68* | − 1.60 | − 2.65 | − 0.79 | − 4.07 |
| P₁×P₄ | 32.75* | 32.21* | 20.74 | 16.87 | 65.88** | 63.08* | 21.72 | 17.32 | 103.33** | 80.76** | − 0.79 | − 0.91 | 3.16 | − 2.39 |
| P₁×P₅ | 14.40 | − 1.28 | − 5.58 | − 17.20 | 19.01 | 10.01 | − 8.60 | − 20.96 | 6.77 | 3.31 | − 17.7 | − 21.53 | − 18.76 | − 23.34 |
| P₁×P₆ | 32.48 | 20.85 | 14.68 | − 3.88 | 30.87 | 15.22 | 13.24 | − 5.98 | 33.57 | 26.24 | − 22.69 | − 23.21 | − 9.68 | − 10.19 |
| P₁×P₇ | 43.72* | 31.64* | 19.40 | 6.67 | 17.52 | 19.08 | 27.50 | 2.65 | 55.99** | 33.54 | − 11.34 | − 20.68 | − 4.73 | − 6.87 |
| P₁×P₈ | 18.82 | 7.44 | 4.99 | − 1.66 | 15.57 | 14.79 | 8.34 | 2.01 | 77.09** | 74.07** | − 3.50 | − 5.75 | − 2.84 | − 4.46 |
| P₁×P₉ | − 6.28 | − 7.31 | 6.90 | − 4.97 | − 3.71 | − 10.03 | 7.32 | − 7.83 | 49.27* | 35.33 | − 8.91 | − 11.71 | − 6.59 | − 8.93 |
| P₂×P₃ | 86.42** | 58.17** | 48.83** | 24.85 | 11.22 | − 10.74 | 91.94** | 69.82** | 24.74 | 7.12 | − 29.6 | − 38.27 | 0.19 | − 2.57 |
| P₂×P₄ | 37.54 | 10.02 | 33.97 | 9.87 | 46.66 | 33.66 | 48.60** | 26.93 | 85.00** | 62.09* | − 20.11 | − 29.22 | 0.93 | − 3.96 |
| P₂×P₅ | 60.27* | 45.81* | 36.20 | 29.89 | 35.15 | 30.87 | 56.74** | 48.97** | 41.54 | 9.51 | − 17.10 | − 29.61 | − 1.51 | − 6.54 |
| P₂×P₆ | 34.01 | 15.35 | 48.26* | 47.41 | 24.17 | 21.50 | 47.93** | 47.55* | 30.20 | − 0.98 | 8.95 | − 3.01 | − 5.27 | − 5.29 |
| P₂×P₇ | 61.86** | 38.79** | 31.51 | 22.93 | 26.19 | 11.96 | 53.63** | 48.13* | 52.07** | 7.72 | 0.27 | − 0.96 | − 7.12 | − 8.67 |
| P₂×P₈ | 51.50* | 31.48* | 18.33 | 5.51 | 12.84 | 0.67 | 25.93 | 9.83 | 108.24** | 67.21** | − 33.66 | − 42.48 | 4.92 | 3.76 |
| Continued | | | | | | | | | | | | | | |

15

| Hybrids | FW1 | | FW2 | | DSW | | DFW | | NF | | NS | | SW | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | MPH | BPH | MPH | BPH | MPH | BPH | MPH | BPH | MPH | BPH | MPH | BPH | MPH | BPH | | |
| P₂ × P₉ | − 34.08 | − 46.99 | − 4.66 | − 10.41 | 1.03 | − 3.25 | 3.12 | − 1.22 | 6.48 | − 21.42 | − 25.59 | − 35.91 | 1.64 | − 0.34 | | |
| P₃ × P₄ | 51.33** | 51.33** | 21.51 | 21.51 | 24.69 | 24.69 | 25.74* | 25.74* | 42.51 | 42.51 | − 2.54 | − 2.54 | − 5.79 | − 5.79 | | |
| P₃ × P₅ | 66.14** | 53.72** | 32.33 | 15.59 | 28.18 | 5.48 | 22.39 | 13.47 | 51.15* | 33.23 | − 4.12 | − 7.64 | 1.18 | − 1.34 | | |
| P₃ × P₆ | 16.52 | 14.53 | 10.24 | − 7.95 | 17.72 | − 7.06 | 12.98 | 0.18 | 61.63** | 39.50 | − 7.67 | − 9.26 | − 5.69 | − 8.31 | | |
| P₃ × P₇ | 19.70 | 18.19 | 19.53 | 6.35 | 15.07 | 2.48 | 27.25 | 9.07 | 9.11 | − 13.75 | − 11.29 | − 21.38 | − 1.83 | − 2.93 | | |
| P₃ × P₈ | 50.95* | 46.97* | 10.90 | 3.43 | 19.10 | 5.49 | 6.79 | 5.05 | 73.74** | 60.23* | − 12.29 | − 13.43 | − 12.69 | − 14.17 | | |
| P₃ × P₉ | − 13.98 | − 19.45 | − 1.33 | − 12.64 | 2.88 | − 14.55 | 6.20 | − 2.29 | 19.46 | − 0.65 | − 1.83 | − 3.84 | − 7.11 | − 7.90 | | |
| P₄ × P₅ | 71.51** | 48.51** | 22.62 | 4.58 | 37.23 | 28.88 | 29.91* | 16.03 | 49.97* | 29.55 | − 2.58 | − 7.22 | − 5.57 | − 5.84 | | |
| P₄ × P₆ | 74.52** | 59.79** | 46.16** | 19.33 | 66.04* | 48.39 | 36.11* | 16.51 | 108.72** | 76.64* | − 3.47 | − 3.99 | − 0.12 | − 4.99 | | |
| P₄ × P₇ | 14.24 | 5.03 | − 0.52 | − 13.63 | 20.85 | 17.30 | 14.27 | − 5.29 | − 20.37 | − 38.12 | − 17.34 | − 25.96 | − 12.74 | − 15.61 | | |
| P₄ × P₈ | 34.10 | 21.70 | 26.45 | 14.90 | 44.43 | 41.06 | 20.11 | 17.22 | 26.79 | 14.46 | 0.65 | − 1.82 | − 6.26 | − 9.85 | | |
| P₄ × P₉ | 46.56** | 45.53** | 48.19** | 28.04 | 71.65** | 62.98* | 46.13** | 29.58* | 15.61 | − 5.62 | 1.48 | − 1.76 | 2.63 | − 0.48 | | |
| P₅ × P₆ | − 2.61 | − 8.44 | 13.46 | 7.61 | 26.37 | 19.82 | 20.06 | 14.38 | 9.74 | 7.10 | − 2.84 | − 7.96 | − 9.00 | − 13.66 | | |
| P₅ × P₇ | 37.76 | 28.97 | 29.99 | 27.28 | 4.88 | − 4.20 | 10.25 | 1.22 | 49.22** | 31.42 | 8.53 | − 6.88 | − 2.44 | − 5.91 | | |
| P₅ × P₈ | 91.43** | 81.65** | 56.76** | 46.05* | 57.78* | 44.94 | 52.34** | 39.1* | 51.94* | 44.60 | − 20.8 | − 22.73 | − 14.93 | − 18.41 | | |
| P₅ × P₉ | 25.67 | 9.47 | 9.99 | 8.29 | 28.87 | 27.39 | 30.04 | 28.98 | 30.97 | 22.42 | − 12.74 | − 14.21 | − 3.09 | − 6.29 | | |
| P₆ × P₇ | 16.64 | 16.11 | 12.57 | 4.66 | 6.06 | − 7.66 | 19.94 | 15.36 | 31.50 | 18.35 | − 2.28 | − 12.05 | − 4.06 | − 5.68 | | |
| P₆ × P₈ | 55.95** | 54.44** | 15.71 | 2.65 | 9.03 | − 4.56 | 7.49 | − 6.05 | 75.20** | 62.92** | − 1.00 | − 3.94 | − 4.78 | − 5.84 | | |
| P₆ × P₉ | 44.04* | 32.74* | 27.75 | 19.40 | 31.04 | 22.90 | 33.13* | 27.83 | 67.02** | 59.80** | − 3.99 | − 7.54 | − 8.05 | − 9.85 | | |
| P₇ × P₈ | 24.35 | 22.59 | 14.78 | 9.09 | 14.26 | 13.54 | 10.58 | − 6.51 | 10.77 | − 6.52 | − 19.99 | − 29.89 | − 14.65 | − 15.15 | | |
| P₇ × P₉ | 62.00** | 49.91** | 35.35 | 34.59 | 49.30* | 37.83 | 44.14* | 33.33 | 89.89** | 78.09** | − 9.79 | − 21.48 | − 7.66 | − 7.91 | | |
| P₈ × P₉ | 49.18** | 36.25** | 9.29 | 3.32 | 31.03 | 21.66 | 17.07 | 6.10 | 49.43* | 33.40 | − 1.11 | − 1.88 | − 7.39 | − 8.18 | | |
| Mean | 37.52 | 26.36 | 21.36 | 10.63 | 26.05 | 16.31 | 25.97 | 14.76 | 47.76 | 29.57 | − 9.58 | − 14.87 | − 4.91 | − 7.19 | | |
| LSD5% | 358.38 | 413.82 | 92.18 | 106.44 | 41.34 | 47.74 | 5.89 | 6.80 | 35.50 | 40.99 | 2.65 | 3.06 | 1.69 | 1.95 | | |
| LSD1% | 472.94 | 546.10 | 121.64 | 140.46 | 54.56 | 63.00 | 7.77 | 8.97 | 46.85 | 54.10 | 3.49 | 4.04 | 2.23 | 2.57 | | |

**Table 9.** Estimates of mid-parent and better parent heterosis for 15 characteristics of 36 crosses in kenaf over two environments. *PH* plant height, *BD* base diameter, *CD* core diameter, *MD* middle diameter, *TD* top diameter, *NN* number of nodes, *DTFF* days to 1st flowering, *D50%F* days to 50% flowering, *LSD* least significant difference, *FW1* fresh stem weight with leaves and pod, *FW2* fresh stem weight without leaves and pod, *DSW* dry stick weight, *DFW* dry fiber weight, *NF* number of pods per plant, *NS* number of seeds per pod, *SW* 1000 seeds weight. **Highly significant at P ≤ 0.01 level, *Significant at P ≤ 0.05 level.

| Sl No. | Traits | General combiner | Specific combiner |
|---|---|---|---|
| 1 | Plant height (cm) | P₇ (BJRI Kenaf4) | P₅ (ML36-25) × P₈ (MLRing4P2) |
| 2 | Base diameter (mm) | P₄ (ML36-24) | P₂ (ML9) × P₃ (ML36-10) |
| 3 | Core diameter (mm) | P₄ (ML36-24) | P₂ (ML9) × P₃ (ML36-10) |
| 4 | Middle diameter (mm) | P₄ (ML36-24) | P₅ (ML36-25) × P₇ (BJRI Kenaf4) |
| 5 | Top diameter (mm) | P₄ (ML36-24) | P₆ (ML36-27) × P₇ (BJRI Kenaf4) |
| 6 | Number of nodes | P₁ (ML5) | P₂ (ML9) × P₉ [ML36-21(2)] |
| 7 | Days to first flowering | P₂ (ML9) | P₂ (ML9) × P₅ (ML36-25) |
| 8 | Days to 50% flowering | P₂ (ML9) | P₆ (ML36-27) × P₉ [ML36-21(2)] |
| 9 | Fresh stem weight with leaves and pod (g) | P₄ (ML36-24) | P₂ (ML9) × P₃ (ML36-10) |
| 10 | Fresh stem weight without leaves and pod (g) | P₄ (ML36-24) | P₅ (ML36-25) × P₈ (MLRing4P2) |
| 11 | Dry stick weight (g) | P₄ (ML36-24) | P₇ (BJRI Kenaf4) × P₉ [ML36-21(2)] |
| 12 | Dry fiber weight (g) | P₄ (ML36-24) | P₂ (ML9) × P₃ (ML36-10) |
| 13 | Number of pods per plant | P₇ (BJRI Kenaf4) | P₇ (BJRI Kenaf4) × P₉ [ML36-21(2)] |
| 14 | Number of seeds per pod | P₉ [ML36-21(2)] | P₂ (ML9) × P₆ (ML36-27) |
| 15 | 1000 seeds weight (g) | P₂ (ML9) | P₁ (ML5) × P₅ (ML36-25) |

**Table 10.** Best general and specific combiner for 15 traits.

| Crosses | PH | BD | CD | MD | TD | NN | DTFF | D50%F | FW1 | FW2 | DSW | DFW | NF | NS | SW | Cumulative rank | Position of crosses |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $P_1 \times P_2$ | 6 | 17 | 19 | 15 | 27 | 11 | 29 | 31 | 16 | 19 | 21 | 28 | 17 | 34 | 22 | 312 | 26 |
| $P_1 \times P_3$ | 14 | 7 | 6 | 10 | 7 | 33 | 24 | 17 | 9 | 17 | 19 | 6 | 7 | 4 | 28 | 208 | 3 |
| $P_1 \times P_4$ | 23 | 15 | 14 | 14 | 26 | 22 | 33 | 33 | 18 | 15 | 2 | 16 | 3 | 8 | 35 | 277 | 18 |
| $P_1 \times P_5$ | 34 | 30 | 30 | 36 | 17 | 21 | 3 | 10 | 29 | 34 | 26 | 35 | 34 | 26 | 1 | 366 | 34 |
| $P_1 \times P_6$ | 20 | 22 | 17 | 17 | 12 | 26 | 18 | 21 | 14 | 20 | 8 | 19 | 25 | 36 | 6 | 281 | 20 |
| $P_1 \times P_7$ | 3 | 5 | 5 | 26 | 36 | 30 | 4 | 16 | 8 | 8 | 15 | 7 | 10 | 18 | 20 | 211 | 5 |
| $P_1 \times P_8$ | 10 | 19 | 18 | 24 | 34 | 10 | 22 | 24 | 25 | 28 | 28 | 22 | 11 | 5 | 29 | 309 | 25 |
| $P_1 \times P_9$ | 29 | 31 | 33 | 9 | 5 | 4 | 8 | 2 | 33 | 9 | 36 | 14 | 29 | 12 | 14 | 268 | 15 |
| $P_2 \times P_3$ | 30 | 1 | 1 | 4 | 9 | 36 | 7 | 19 | 1 | 2 | 23 | 1 | 23 | 33 | 19 | 209 | 4 |
| $P_2 \times P_4$ | 2 | 12 | 12 | 8 | 23 | 34 | 5 | 12 | 21 | 16 | 10 | 11 | 8 | 25 | 18 | 217 | 7 |
| $P_2 \times P_5$ | 17 | 8 | 8 | 27 | 35 | 35 | 1 | 4 | 12 | 12 | 7 | 4 | 19 | 20 | 21 | 230 | 9 |
| $P_2 \times P_6$ | 5 | 9 | 9 | 12 | 32 | 29 | 25 | 34 | 20 | 6 | 17 | 12 | 24 | 1 | 10 | 245 | 12 |
| $P_2 \times P_7$ | 11 | 10 | 10 | 21 | 33 | 20 | 34 | 36 | 7 | 13 | 6 | 9 | 14 | 3 | 7 | 234 | 10 |
| $P_2 \times P_8$ | 12 | 25 | 26 | 23 | 15 | 17 | 35 | 28 | 17 | 26 | 30 | 26 | 4 | 35 | 36 | 355 | 32 |
| $P_2 \times P_9$ | 36 | 36 | 36 | 33 | 1 | 1 | 17 | 3 | 36 | 36 | 31 | 36 | 35 | 17 | 12 | 366 | 35 |
| $P_3 \times P_4$ | 13 | 18 | 15 | 20 | 30 | 32 | 16 | 26 | 11 | 21 | 27 | 21 | 21 | 13 | 9 | 293 | 21 |
| $P_3 \times P_5$ | 8 | 26 | 25 | 31 | 22 | 7 | 21 | 11 | 6 | 7 | 5 | 23 | 12 | 10 | 34 | 248 | 13 |
| $P_3 \times P_6$ | 7 | 21 | 21 | 16 | 28 | 15 | 20 | 23 | 30 | 30 | 16 | 30 | 13 | 22 | 15 | 307 | 24 |
| $P_3 \times P_7$ | 9 | 27 | 31 | 25 | 21 | 9 | 23 | 32 | 26 | 18 | 14 | 18 | 30 | 24 | 30 | 337 | 29 |
| $P_3 \times P_8$ | 18 | 13 | 22 | 30 | 24 | 31 | 14 | 18 | 15 | 27 | 13 | 33 | 9 | 23 | 4 | 294 | 22 |
| $P_3 \times P_9$ | 32 | 35 | 35 | 22 | 11 | 2 | 11 | 6 | 35 | 33 | 25 | 34 | 27 | 15 | 8 | 331 | 28 |
| $P_4 \times P_5$ | 24 | 11 | 13 | 6 | 18 | 18 | 31 | 20 | 5 | 23 | 29 | 17 | 15 | 11 | 16 | 257 | 14 |
| $P_4 \times P_6$ | 21 | 4 | 4 | 13 | 31 | 28 | 36 | 35 | 2 | 3 | 4 | 10 | 2 | 19 | 31 | 243 | 11 |
| $P_4 \times P_7$ | 27 | 32 | 34 | 18 | 3 | 14 | 15 | 7 | 31 | 35 | 33 | 31 | 36 | 31 | 2 | 349 | 31 |
| $P_4 \times P_8$ | 15 | 6 | 7 | 19 | 8 | 25 | 2 | 14 | 23 | 14 | 12 | 20 | 28 | 7 | 13 | 213 | 6 |
| $P_4 \times P_9$ | 28 | 24 | 23 | 32 | 10 | 3 | 13 | 9 | 27 | 5 | 18 | 8 | 33 | 21 | 27 | 281 | 19 |
| $P_5 \times P_6$ | 4 | 29 | 27 | 28 | 25 | 8 | 28 | 30 | 34 | 31 | 22 | 25 | 31 | 14 | 11 | 347 | 30 |
| $P_5 \times P_7$ | 19 | 23 | 24 | 11 | 19 | 13 | 26 | 27 | 19 | 10 | 35 | 32 | 5 | 2 | 32 | 297 | 23 |
| $P_5 \times P_8$ | 1 | 2 | 2 | 1 | 4 | 16 | 10 | 29 | 3 | 1 | 3 | 2 | 16 | 32 | 5 | 127 | 1 |
| $P_5 \times P_9$ | 33 | 33 | 32 | 29 | 14 | 12 | 32 | 22 | 32 | 32 | 20 | 15 | 20 | 28 | 33 | 387 | 36 |
| $P_6 \times P_7$ | 26 | 14 | 11 | 7 | 2 | 19 | 9 | 15 | 24 | 29 | 32 | 24 | 22 | 16 | 25 | 275 | 17 |
| $P_6 \times P_8$ | 25 | 16 | 16 | 35 | 20 | 6 | 6 | 8 | 10 | 24 | 34 | 29 | 6 | 9 | 24 | 268 | 16 |
| $P_6 \times P_9$ | 31 | 20 | 20 | 5 | 6 | 23 | 12 | 1 | 13 | 11 | 9 | 5 | 18 | 29 | 17 | 220 | 8 |
| $P_7 \times P_8$ | 16 | 28 | 28 | 34 | 29 | 5 | 30 | 25 | 28 | 22 | 24 | 27 | 32 | 30 | 3 | 361 | 33 |
| $P_7 \times P_9$ | 22 | 3 | 3 | 2 | 13 | 24 | 19 | 5 | 4 | 4 | 1 | 3 | 1 | 27 | 23 | 154 | 2 |
| $P_8 \times P_9$ | 35 | 34 | 29 | 3 | 16 | 27 | 27 | 13 | 22 | 25 | 11 | 13 | 26 | 6 | 26 | 313 | 27 |

**Table 11.** Rank positions of the $F_1$s based on 15 morpho-physiological characters. The lowest value for each character indicates the best one, *PH* plant height, *BD* base diameter, *CD* core diameter, *MD* middle diameter, *TD* top diameter, *NN* number of nodes, *DTFF* days to 1st flowering, *D50%F* days to 50% flowering, *FW1* fresh stem weight with leaves and pod, *FW2* fresh stem weight without leaves and pod, *DSW* dry stick weight, *DFW* dry fiber weight, *NF* number of pods per plant, *NS* number of seeds per pod, *SW* 1000 seeds weight.

for quality fiber yield, and cross $P_1 \times P_5$ with the lowest negative heterosis for 1000 seed weight ($-18.76$) would produce well where smaller seed size kenaf accessions perform well.

**Heterobeltiosis response exposed to a pooled environment.** Overdominance for heterobeltiosis was seen in the most outstanding crosses $P_2 \times P_3$ and $P_2 \times P_5$ for fiber yield and the crosses $P_1 \times P_4$ and $P_4 \times P_9$ for stick yield, as shown in Table 9, since their heterobeltiosis values were very significant positive with high potence ratio. Due to the presence of over dominance, the seed yield crosses $P_1 \times P_4$, $P_1 \times P_8$ and $P_7 \times P_9$ were chosen for pods number per plant. Overdominance for heterobeltiosis, as indicated by the potence ratio, was found in the promising crosses $P_2 \times P_3$, $P_5 \times P_8$ and $P_7 \times P_9$ for base diameter and core diameter, cross $P_6 \times P_7$ for top diameter, cross $P_5 \times P_8$ for middle diameter, fresh stem weight with leaves and pods, and fresh stem weight without leaves and pods, and cross $P_4 \times P_6$ for base diameter, core diameter, fresh stem weight with leaves and pods, and pods number per plant. In terms of node number and seed weight, negative heterosis is preferable. Meanwhile, in terms of percentage $F_1$ heterosis above high parent in node number and 1000 seed weight, crosses $P_2 \times P_9$ and $P_1 \times P_5$ had the lowest negative heterosis values, respectively.

**Selection of best parents and offspring.** The yield and yield contributing components of fifteen parents and crosses were investigated in this study. Table 10 lists the best general and specific combiners based on trait performance. It's always possible that some crosses will work better in some characters than others. To determine the most favorable, rate each on a character-by-character basis and see which ones perform better across the range. When the SCA results of 36 crosses were reviewed, the cross $P_5 \times P_8$ was shown to be the best in ranking for all the characters. $P_7 \times P_9$, $P_1 \times P_3$, $P_2 \times P_3$, $P_1 \times P_7$, $P_4 \times P_8$, and $P_2 \times P_4$ were the next crosses (Table 11). This was possibly due to their greater distance from the others. The performance of the cross $P_5 \times P_9$ was determined to be extremely low. This was because these two genotypes are the most similar. However, based on their cumulative rating, ten superior crossings were selected for inclusion in a future breeding effort. Thirty-six kenaf $F_1$s were arrayed in order of merit, with the rank total against the crosses indicating the lot's position.

## Discussion

The wide variation in the crop's botanical and agro morphological properties suggests that the genotypes are genetically diverse (Ogunniyan, 2016). Segregation was seen in 36 crosses for stem color, leaf shape, leaf color (lamina), petiole color, pod shape, seed shape, and seed coat color in the $F_1$ generation (Supplementary Fig. 1). In addition, some of the crosses indicated significant differences in leaf shape and pigmentation pattern on the stem and petiole (Table 3). Indeed, the green morphotype kenaf leaves are more valuable for their food value, and their fibers are better for stringing[22]. The parents had green, green with reddish patches, and purple stem color, however the cross combinations had green, green with reddish patches, purple, reddish above greenish below, reddish, and red stem color. When the upper surface light reddish but lower surface green pigmented parent $P_7$ was crossed with the rest of the green parents, the $F_1$ showed various pigmentation patterns on the petiole, including green, upper surface light reddish but lower surface green, reddish, and purple. When the ash gray, brownish, and black with few brownish seed coat color parents crossed, $F_1$ offspring with blackish, ash gray, brownish, and black with few brownish seeds were produced, as were those observed by Osman et al. (2011). In addition, the leaf shape, leaf color (lamina), pod shape, and seed shape of selected parents and their $F_1$ hybrids showed a wide range of diversity.

Table 4 shows the results of the mean squares analysis of variance on the combined data of the two environments, which revealed that, except for middle diameter, the effects of the environments were highly significant ($p \leq 0.01$). The genotypes performed differently across the environments studied, based on the analysis results on the combined data. The effects of genotype by environment interaction were highly significant ($p \leq 0.01$) for all traits measured except for plant height, and significant ($p \leq 0.05$) for days to first flowering. These results indicate that the effects of genes controlling these traits were expressed differently at different environments. The mean squares of GCA were bigger than the mean squares of SCA for all traits except top diameter, nodes number, and fresh stem weight with leaves and pods in our investigation indicating that the parental materials studied had a lot of genetic variability. Due to the presence of large additive gene effects, this result usually favors the selection strategy of breeding[39,40]. Days to first flowering, dry fiber weight and 1000-seed weight were found to indicate the prevalence of additive gene effects in the development of the features by Mostofa et al.[29]. For seed yield per plant and number of pods per plant in kenaf, Mukewar et al.[31] found that additive gene action predominated. For yield components such as plant height, fresh and dry weight of bark, and usable stick in kenaf, Pace et al.[32] found additive gene action was more relevant. All the analyzed variables (except top diameter and node number) had large mean square GCA values, indicating that the parental materials studied had a lot of genetic variability. All the examined parameters (excluding plant height, days to 50% flowering, fresh stem weight without leaves and pod) showed a very significant effect on GCA environment interaction, indicating that environmental variation influenced additive gene action. Furthermore, environments had a significant influence on how these characters changed[1]. Using combining ability investigations, Mostofa et al.[30] and Youcai et al.[49] found similar results in *Hibiscus cannabinus*, Sobhan[43] in *Hibiscus sabdariffa*, and Khatun[23] in *Corchorus capsularis*.

Table 4 shows that except for plant height and seeds number per pod, genotypes and environment interaction were highly significant in the pooled quantitative data showed that the environment significantly impacted both parents and offspring for all attributes. We employed nine kenaf genotypes with a range of morpho-physiological and yield features. The mean squares of GCA were bigger than the mean squares of SCA for all traits except top diameter, nodes number, and fresh stem weight with leaves and pods in our investigation indicating that the parental materials studied had a lot of genetic variability. Due to the presence of large additive gene effects, this result usually favors the selection strategy of breeding[39,40]. Days to first flowering, fibre weight per plant, and 1000-seed weight were found to indicate the prevalence of additive gene effects in the development of the features by Mostofa et al.[29]. Days to first flowering and plant height were controlled by one dominant gene pair, while raw fibre yield was controlled by three (Thombre and Patil, 1985). For seed yield per plant and number of pods per plant in kenaf, Mukewar et al.[31] found that additive gene action predominated. For yield components such as plant height, fresh and dry weight of bark, and usable stick in kenaf, Pace et al.[32] found additive gene action was more relevant. When both general and specific combining ability effects are essential, Comstock et al. (1949) suggested using a reciprocal recurrent selection strategy to generate high yielding varieties. All the examined parameters (excluding plant height, days to 50% flowering, fresh stem weight without leaves and pod) showed a very significant effect on GCA environments, indicating that environmental variation influenced additive gene action. Furthermore, environments had a big influence on how these characters changed[1].

The findings revealed that environmental influences controlled the expression of kenaf phenotypic features. The mean of hybrids is higher than the parental mean for plant height, base diameter, core diameter, middle diameter, top diameter, number of nodes, fresh stem weight with leaves and pod, fresh stem weight without leaves and pod, dry stick weight, dry fiber weight, and pods number per plant. In comparison to their parents, hybrids have higher fiber and stick yields and a higher seed yield. Days to first flowering and days to 50% flowering of

hybrids, on the other hand, were lower than the parental mean. However, the mean hybrid of 1000 seeds weight had a lower mean value than the parental mean, indicating that smaller seed size hybrids were preferable to parents, but that when the nodes number was larger than the parental mean, the fiber production per plant was reduced. Parent $P_1$ had the highest fiber weight per plant (26.71 g) among the parental lines, followed by $P_4$ (24.78 g), and $P_8$ (23.59 g). Similarly, the hybrids $P_2 \times P_3$, $P_4 \times P_6$, and $P_5 \times P_8$ had much greater fiber yield (38.74 g, 28.87 g, and 32.81 g, respectively) than their respective parents. Parent $P_3$ produced the meanest stick weight per plant (123.24 g), followed by $P_7$ (96.27 g), and $P_8$ (95.06 g). The hybrids $P_1 \times P_4$, $P_5 \times P_8$, and $P_7 \times P_9$ generated the highest mean stick weight per plant (152.93 g, 137.78 g, and 132.68 g, respectively), which was significantly higher than both parents. The cross combinations $P_1 \times P_4$, $P_4 \times P_6$, and $P_7 \times P_9$ produced the most pods per plant (157, 172 and 217, respectively), far exceeding any of the parents, demonstrating the presence of transgressive segregation in the cross.

The results of combining ability analysis are used to select parents and crosses. However, the nature of gene action revealed that both additive and non-additive gene effects were crucial in governing the diverse characters of kenaf in this investigation, but non-additive gene action was shown to control most of the characters. Gupta and Singh[16] state that non-additive gene activity affects plant height, basal stem diameter, fiber weight per plant, and stick weight per plant (*H. sabdariffa*). Non-additive gene action predominated for all other parameters except days to first flowering, dry fiber weight, and 1000 seed weight. Through pedigree and single seed descent methods of breeding, it is possible to improve traits with a predominance of additive genetic effects. When non-additive gene effects predominated, however, bi-parental mating and a recurrent selective breeding system would be an effective way to obtain hybrid diversity.

Parents' breeding potential is usually linked to their GCA effects. Parents having high GCA effects for certain qualities could be employed as donor parents in hybridization programs to increase these features. A low or negative combining ability effect reflects a plant's inability to pass on its genetic superiority to hybrids[10]. Positive values with the highest magnitudes have the most impact. On the other hand, the greatest negative values have the least impact[44]. Additive genetic variance is a major contributor to the GCA component. As a result, each parent's GCA variation has a major impact on the parents' decisions. A good general combiner is a parent with a higher positive significant GCA effect[36]. In this study, GCA's high value for the traits of interest was distributed across genotypes, showing that none of the genotypes used had the optimal combination of GCA values for the several characters of interest.

Parent $P_4$ (ML36-24) was the best parental line in terms of base diameter, core diameter, middle diameter, fresh stem weight with leaves and pod, fresh stem weight without leaves and pods, dry stick weight, and dry fiber weight content, showing the accumulation of favorable additive genes for these traits in the hybrid. The parent $P_3$ had positive effects on plant height, fresh stem weight without leaves and pods, dry stick weight, and dry fiber weight, conversely the parent $P_1$ was the good general combiner for days to first flowering and dry fiber weight, and it contributed positively to the hybrid for these traits. The major goal of this breeding program is to develop high-yielding hybrids with high potential fiber production as compared to existing cultivars or on par with them. As a result, for fiber yield per plant, parent $P_4$ might be well combined. Furthermore, the parent $P_3$ had positive effects on plant height, fresh stem weight without leaves and pods, dry stick weight, and dry fiber weight, and the parent $P_1$ was the best general combiner for days to first flowering, dry fiber weight, and number of pods per plant. Other parents are specialized in one or two characteristics. To put it briefly, the parental lines $P_1$, $P_3$, and $P_4$ were determined to be outstanding general combiners for fiber yield and yield-related parameters. Parents $P_3$ and $P_4$ were good general combiners in terms of stick yield. The parents $P_1$, $P_6$ and $P_7$, on the other hand, were good general combiners for seed yield (pods number per plant). In contrast, parent $P_2$ was chosen as a good general combiner for the first flowering and days to 50% flowering features, which are important for late maturity cultivars. Golam et al.[14] found that 50% flowering and days to maturity, in addition to other morpho-agronomic features, may be the two most important variables in classifying kenaf accessions.

Parents with a high GCA for a certain trait and high adaptability indicate additive gene action. Because additive variance may be fixed, selecting for qualities regulated by additive variance is a very effective strategy[35]. The parents $P_3$ and $P_4$ were found to be the finest general combiners, with extremely significant values for fresh stem weight without leaves and pod, dry stick weight, and dry fiber weight, all of which are more suitable for desired kenaf features such as bast fiber and core fiber production. The parents with the highest GCA values (strong GCA effects) could be used to improve the kenaf population in Malaysia through varietal development based on desirable features.

In general, crosses with high × low general combiners for yield components outperform others. According to an investigation of combining ability impacts, high specific combiners involved high × high, high × low, high × average, average × average, average × low, and low × low combining parents. In crosses with high × low and low × low general combiners, Jinks[21] described severe SCA effects caused by over-dominance and epistasis. In crosses involving high vs. low general combiners for yield components, mutual cancellation of heterosis components, especially dominance and its interaction, resulting in unfavorable SCA effects[17]. Crossing two parents with low general combiners produces high performance, attributable to complementary gene activity[27]. This study, SCA effects were shown to be significant for most yield characteristics. For base diameter, core diameter, fresh stem weight with leaves and pod, and fresh stem weight without leaves and pod, the best crossings suggested by SCA effects (Table 8) were $P_2 \times P_3$, $P_4 \times P_6$, and $P_5 \times P_8$.

In contrast, the hybrids $P_2 \times P_3$ and $P_5 \times P_8$ were shown to be the best specific combiners for fiber yield, with high base diameter, core diameter, fresh stem weight with leaves and pod, and fresh stem weight without leaves and pod features. Furthermore, for stick yield and seed yield (plant number of pods), the hybrids $P_1 \times P_4$ and $P_7 \times$ were chosen as the best specific combiners. The hybrid $P_2 \times P_5$ will be the best choice for 1st flowering and days to 50% flowering attributes in late maturity cultivars. In terms of another feature, the rest of the hybrids performed better. The strongest positive estimations of mid-parent and better parent heterosis for the qualities

examined, indicating the accumulation of favorable genes inherited from their parental inbred lines. Among the hybrids produced, $P_2$ (ML9) × $P_3$ (ML36-10), $P_5$ (ML36-25) × $P_8$ (MLRing4P2), $P_4$ (ML36-24) × $P_6$ (ML36-27), $P_1$ (ML5) × $P_4$ (ML36-24), $P_7$ (BJRI Kenaf4) × $P_9$ [ML36-21(2)], $P_2$ (ML9) × $P_5$ (ML36-25), $P_2$ (ML9) × $P_9$ [ML36-21(2)] and $P_1$ (ML5) × $P_5$ (ML36-25) had higher yield and yield component qualities indicated by hybrids evaluated based on pooled data from the two environments.

The hybrids $P_1 × P_4$, $P_4 × P_6$ and $P_7 × P_9$ were chosen as the best specific combiners for dry stick weight and pods number per plant. Days to first flowering and days to 50% flowering for the hybrid $P_2 × P_5$ were also chosen as unique combiners. The best specific combiners for dry fiber weight and seeds number per pod were hybrid $P_1 × P_3$. For pods per plant and seeds per pod, the hybrids $P_1 × P_4$ and $P_5 × P_7$ were selected as good specific combiners. For another required attribute 1000 seed weight, the hybrids $P_1 × P_5$, $P_3 × P_8$, $P_4 × P_7$, and $P_7 × P_8$ were chosen as good specific combiners (smaller seed size). The data revealed that the GCA effects of parents were linked to the SCA impacts of their crossings, which had the greatest significant positive intensity. Complementing gene effects could explain the strong SCA effects of these crosses. Hybrid vigor can be induced by dominant, over-dominant, or epistatic gene action in any combination of parents, according to Moll and Stuber[28]. In this study, both additive and non-additive genetic components influenced morphological and yield-related traits, with non-additive gene activity dominating most of the characters.

Table 9 shows estimates of mid-parent and better parent heterosis for yield and yield component qualities indicated by hybrids evaluated based on pooled data from the two environments. Liu[25] reported heterosis in yield characteristics based on the mid-parent and better parent. Heterosis estimates based on mid parental values were generally high, with stalk dry weight and bast percentage ranging from 10 to 55%[4]. The strongest positive estimations of mid-parent and better parent heterosis for the qualities examined were derived from $P_4 × P_6$ based on the combined data of the two environments (108.72% and 76.64%, respectively, for the pods number per plant). Hybrid $P_2 × P_3$ showed the greatest mid-parent and better parent heterosis for 4 of the 15 phenotypic parameters measured, including base diameter, core diameter, fresh stem weight with leaves and pods, and dry fiber weight, based on the combined data from the two environments.

In addition, hybrid $P_5 × P_8$ had the second highest mid-parent and better parent heterosis for base diameter, core diameter, middle diameter, fresh stem weight with leaves and pods, fresh stem weight without leaves and pods, and dry fiber weight, as well as $P_4 × P_6$ for base diameter, core diameter, fresh stem weight with leaves and pods, and pods number per plant. In terms of the features indicated, these hybrids outperformed their inbred parents. Hybrid $P_7 × P_9$ showed the better mid-parent and better parent heterosis for base diameter, core diameter, fresh stem weight with leaves and pods, and pods number per plant based on the combined data. Furthermore, the hybrid $P_1 × P_4$ was chosen as the best combiners for stick yield and pods number per plant, whereas hybrid $P_4 × P_9$ for stick yield and fiber yield showed the greatest mid-parent and better parent heterosis. In late maturity cultivars, the hybrid $P_1 × P_9$ will be the best choice for 1st flowering and days to 50% flowering features.

In contrast, hybrid $P_2 × P_9$ for Plant height, base diameter, core diameter, and fresh stem weight with leaves and pods showed low mid-parent and better parent heterosis estimates, followed by $P_1 × P_5$ for middle diameter, fresh stem weight without leaves and pods, and dry fiber weight, where the high values were unfavorable. Higher heterosis values compared to the better parent and the mid-parent suggested the absence of epistasis and the frequency of partial or total dominance of genes for fiber and seed yield. Crosses that produce superior transgressive segregants with higher fiber production could be found by looking at the percent $F_1$ heterosis over the high parent.

The strongest positive estimations of mid-parent and better parent heterosis for the qualities examined, indicating the accumulation of favorable genes inherited from their parental inbred lines. Among the hybrids produced, $P_2$ (ML9) × $P_3$ (ML36-10), $P_5$ (ML36-25) × $P_8$ (MLRing4P2), $P_4$ (ML36-24) × $P_6$ (ML36-27), $P_1$ (ML5) × $P_4$ (ML36-24), $P_7$ (BJRI Kenaf4) × $P_9$ [ML36-21(2)], $P_2$ (ML9) × $P_5$ (ML36-25), $P_2$ (ML9) × $P_9$ [ML36-21(2)] and $P_1$ (ML5) × $P_5$ (ML36-25) had higher yield and yield component qualities indicated by hybrids evaluated based on pooled data from the two environments. Both additive and non-additive genetic components were essential in the control of many morphological and yield-related characters, with non-additive gene activities predominating for most of the characters.

## Conclusion

Additive and non-additive variations played a role in the genetic control of all variables in this study, including fiber yield and yield-related traits. New high-yielding kenaf hybrid types could be released via diallel selective mating or mass selection with simultaneous random mating. GCA effects were higher than SCA effects, except for top diameter, node number, and fresh stem weight with leaves and pod, as demonstrated by mean squares, showing that additive gene action predominates for these traits. Fiber yield and seed yield (number of pods per plant) are two important characteristics of kenaf production. Parent $P_4$ (ML36-24) was the best general combiner for fiber yield (bast fiber) based on GCA performance, followed by $P_1$ (ML5) and $P_3$ (ML36-10). Conversely, $P_4$ (ML36-24) was the best general combiner for stick yield (core fiber), followed by $P_3$ (ML36-10). For the number of pods per plant (seed yield), $P_7$ (BJRI Kenaf4) was shown to be the best general combiner, followed by $P_6$ (ML36-27) and $P_1$ (ML5). For days to 1st flowering and days to 50% flowering qualities, $P_2$ (ML9) was chosen as an excellent general combiner. In a breeding programme, the hybrids $P_2$ (ML9) × $P_3$ (ML36-10), $P_4$ (ML36-24) × $P_6$ (ML36-27), and $P_5$ (ML36-25) × $P_8$ (MLRing4P2) will be the best for bast fiber and $P_1$ (ML5) × $P_4$ (ML36-24), $P_5$ (ML36-25) × $P_8$ (MLRing4P2), and $P_7$ (BJRI Kenaf4) × $P_9$ [ML36-21(2)] will be the best for core fiber if fiber yield is the most significant selection factor. If seed yield is important in the breeding programme, the hybrids $P_1$ (ML5) × $P_4$ (ML36-24), $P_4$ (ML36-24) × $P_6$ (ML36-27), and $P_7$ (BJRI Kenaf4) × $P_9$ [ML36-21(2)] will be the best choices for number of pods per plant, and the hybrid $P_2$ (ML9) × $P_5$ (ML36-25) will be the best choice for days to first flowering and days to 50% flowering traits for late maturity cultivars. Crossings of $P_1$

(ML5) × P$_4$ (ML36-24), P$_1$ (ML5) × P$_9$ [ML36-21(2)], P$_2$ (ML9) × P$_3$ (ML36-10), P$_2$ (ML9) × P$_5$ (ML36-25), P$_4$ (ML36-24) × P$_6$ (ML36-27), P$_4$ (ML36-24) × P$_7$ (BJRI Kenaf4), P$_4$ (ML36-24) × P$_9$ [ML36-21(2)], P$_5$ (ML36-25) × P$_8$ (MLRing4P2), and P$_7$ (BJRI Kenaf4) × P$_9$ [ML36-21(2)] showed promising heterotic responses and could benefit future breeding programs.

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Conceptualization, M.A.-M. and M.Y.R.; data curation, M.A.-M. and M.M.H.K.; data analysis, M.A.-M, M.Y.R and Y.O.; funding acquisition, M.A.-M. and M.Y.R.; investigation and supervision, M.Y.R., Z.B., A.M. and Z.A.; writing—original draft, M.A.-M.; writing—review and editing, Y.O. All authors have read and agreed to the published version of the manuscript.

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## Additional information

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