

**Research Article**

Optimizing Gibberellic Acid Application to Enhance Seed Yield and Quality in Kenaf (*Hibiscus cannabinus* L.) under Top-Cutting Management

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Abstract

Kenaf (*H. cannabinus* L.) is an economically important bast fibre crop whose seed production is often constrained by poor flowering, pod set and inconsistent seed quality under late-season cultivation in Bangladesh. This study aimed to evaluate the effect of foliar gibberellic acid (GA₃) applications on growth, yield and seed quality of two improved varieties (BJRI Kenaf 4 and BJRI Kenaf 5) under a standardized top-cutting regime. A two-factor factorial field experiment was conducted in a randomized complete block design with three replications during the *kharif-late* season. Treatments comprised five GA₃ concentrations (25, 50, 75, 100 and 125 ppm) with an untreated control (0), applied twice at 7 and 14 days after top-cutting (30 DAT). Results indicated significant varietal, GA₃ and interaction effects on plant growth, reproductive traits and seed quality. Plant height increased progressively up to 75 ppm GA₃ (224–226 cm) before declining at higher concentrations. Branch number per plant peaked at 75–100 ppm (8.0–8.2 branches), with similar trends observed for pods per plant (50–52 pods), seeds per pod (28–29) and thousand-seed weight (32–32.5 g). Seed yield was maximized at 75 ppm GA₃, reaching 1450–1470 kg ha⁻¹, representing a 70% increase over the untreated control. Seed quality attributes improved with GA₃, with germination percentage (96–97%) and vigor index (≈2050) peaking at 100 ppm, while electrical conductivity of seed leachates was lowest at 75 ppm, indicating superior membrane integrity. Correlation analysis revealed strong positive associations between seed yield and plant height ($r = 0.87$), thousand-seed weight ($r = 0.82$), and vigor index ($r = 0.76$), highlighting their utility as selection criteria for yield improvement. Overall, moderate GA₃ concentrations (50–75 ppm) were most effective for enhancing seed yield and quality in kenaf under top-topping management. These findings provide a practical, low-cost strategy for improvement of kenaf seed production and offer a physiological basis for integration of GA₃ into varietal improvement and seed technology programs.

Keywords: Kenaf, Hibiscus Cannabinus, Gibberellic Acid, Top-Cutting, Seed Yield, Seed Quality, BJRI.

1. Introduction

Kenaf (*H. cannabinus* L.) is a fast-growing annual bast fibre crop of increasing economic and ecological importance. It has gained global attention as a sustainable source of fibre for paper, textiles, biocomposites and bioenergy, while also offering value through seed-derived oil and protein [1]. In South and Southeast Asia, particularly in Bangladesh, the expansion of kenaf has been constrained not only by biotic and abiotic stresses but also by the limited and inconsistent availability of high-quality seed. Despite the release of improved varieties and government investment through the Bangladesh Jute Research Institute (BJRI), seed supply continues to be a critical bottleneck [2]. The challenge is most

evident under late-season production, where short-day photoperiod and weather variability often hinder flowering, pod set and seed maturation.

Kenaf seed production systems have evolved to include direct seeding, transplanting and canopy management interventions such as top or stem cutting, widely referred to as “de-topping” [3]. De-topping is typically performed around 30 days after transplanting (DAT), when the apical meristem is removed to break apical dominance and release lateral buds. This stimulates the emergence of primary branches, thereby increasing pod-bearing sites. Studies in Bangladesh have repeatedly shown that de-topping enhances the number of

pods per plant, seed germination percentage and seedling vigor compared with uncut plants, to underline the importance of canopy management in seed-oriented kenaf cultivation [2, 4].

However, canopy management alone is insufficient to guarantee high seed yield and quality under variable field conditions. Plant growth regulators, particularly gibberellic acid (GA₃), offer a complementary strategy to manipulate growth and reproductive processes. GA₃ is a naturally occurring phytohormone that regulates stem elongation, internodal extension, floral initiation and reproductive development across a wide range of crops [5]. In kenaf, GA₃ has been shown to alter both vegetative and fibre-related traits, but excessive or poorly timed applications can inhibit flowering and reduce reproductive success [6]. This dual effect highlights the importance of optimizing GA₃ application in relation to developmental stage and concentration for seed production objectives.

Evidence from diverse crops demonstrates that foliar-applied GA₃, when delivered at appropriate phenophases, can significantly enhance reproductive development and seed formation. For example, optimized foliar schedules improved seed yield in cauliflower, indicating the critical importance of aligning concentration with growth stage [7]. Similarly, seed priming or foliar GA₃ at modest concentrations, typically between 50 and 100 ppm, has been shown to increase seed germination percentage, seedling vigor and subsequent biomass accumulation in several species, while supra-optimal concentrations often result in negative effects [8, 9]. In closely related *Hibiscus* species such as roselle (*Hibiscus sabdariffa* L.), application of GA₃ at 100 ppm increased seed weight per plant, providing a translational expectation for kenaf [1, 10].

Recent progress in Bangladesh has introduced improved kenaf varieties through BJRI, with BJRI Kenaf 4 released in 2017 and BJRI Kenaf 5 approved in 2023. These varieties were developed to enhance adaptation, stress tolerance and fibre productivity, while offering the potential for greater seed yield stability [11]. Despite these advances, no standardized GA₃-based seed production protocols exist for these cultivars, particularly under de-topping regimes. Thus, integrating canopy management with carefully optimized GA₃ treatments presents a novel avenue to improve both seed yield and seed quality in these new genetic backgrounds [12].

Agronomic practices also strongly interact with growth regulator responses. For instance, sowing window, row spacing and fertilization regimes significantly affect pod set and seed yield in kenaf. Earlier studies found that late-season sowing combined with closer spacing of approximately 30 × 15 cm produced favorable outcomes for de-topped crops [2]. By contrast, when top-cutting was performed under suboptimal planting dates, seed yield was often reduced despite increased branching, suggesting that canopy manipulation alone is insufficient without agronomic alignment [6]. Therefore, the interaction between GA₃ application, de-topping and baseline agronomy must be carefully synchronized to maximize benefits.

The physiological basis of GA₃ action further supports this integrated approach. Moderate concentrations enhance internode elongation, promote axillary bud release and

improve reproductive sink strength, thereby facilitating pod initiation and seed set. However, excessive GA₃ often disrupts hormonal balance, prolongs vegetative growth at the expense of reproductive development and can even increase susceptibility to lodging [5, 13]. Such biphasic responses underscore why identifying an optimal concentration window, likely between 50 and 100 ppm in kenaf—is essential for practical recommendations.

Globally, similar findings reinforce these expectations. In bhendi (*Abelmoschus esculentus*), foliar GA₃ application improved plant height, branch number and seed yield up to a certain threshold, beyond which performance declined [14]. In cotton and sesame, GA₃ applications enhanced reproductive traits, but excessive levels reduced capsule set and seed quality [15, 16]. These consistent observations across species suggest that GA₃ responses are broadly conserved but require genotype-specific calibration.

In this context, BJRI Kenaf 4 and BJRI Kenaf 5 represent promising test cases for refining seed production technologies in Bangladesh. Both varieties have demonstrated improved adaptability, but their responses to GA₃ under standardized de-topping remain undocumented. Moreover, the broader challenge of ensuring a reliable seed supply for kenaf expansion highlights the practical significance of such research. With demand for sustainable fibre crops rising and kenaf playing an increasingly important role in diversified cropping systems, developing optimized seed production packages is vital for both farmers and industries.

Therefore, the present study was designed to evaluate the influence of different foliar GA₃ concentrations on the growth, yield and seed quality of two improved kenaf varieties under a standardized top-cutting protocol at 30 DAT. A factorial field experiment was conducted using five GA₃ concentrations plus a control, applied at critical post-cutting stages. The study aimed to evaluate the effects of GA₃ on growth, reproductive traits, seed yield and quality in BJRI Kenaf 4 and BJRI Kenaf 5 to identify the most effective concentration for seed production. The findings are expected to guide improved seed production practices and support the sustainable expansion of kenaf cultivation in Bangladesh.

2. Materials and Methods

2.1 Experimental site and season

The experiment was carried out at the Jute Agriculture Experiment Station (JAES), BJRI, where kenaf is regularly grown for seed production. The trial was conducted during the kharif-late season (July to December). The land was prepared following standard methods. Fertilizers were applied based on soil test results, following BJRI recommendations (about N100–P10–K60–S20 kg ha⁻¹).

2.2 Experimental design

The experiment followed a two-factor factorial arrangement in a RCBD with three replications, comprising 12 treatment combinations formed by Factor A (Variety: BJRI Kenaf 4 and BJRI Kenaf 5) and Factor B (GA₃ foliar concentration: 0, 25, 50, 75, 100, and 125 ppm); treatments were randomized within each block, giving a total of 36 unit plots, each

measuring 4 m × 3 m (12 m²) with crop geometry of 30 cm between rows and 15 cm between plants; border rows functioned as guards to minimize edge effects.

2.3 Crop establishment and GA₃ application:

Crop establishment was done by seedlings transplantation from direct seeding to maintain the target spacing, and a uniform plant stand was ensured with proper weed and pest management as per BJRI practice manuals. Top-cutting (de-topping) was carried out at 30 DAT by removal of apical 10–12 cm portion or cutting just above the 7th–8th node to release axillary buds and encourage branching for pod setting. GA₃ solutions were prepared by dissolved GA₃ crystals in a small volume of 95% ethanol and then brings to the required volume with clean water containing 0.05% non-ionic surfactant. Foliar applications were done twice at 7 and 14 days after top-cutting (DATC) through spraying to runoff, targeting the newly emerged lateral branches. Applications were carried out during cool morning or evening hours when wind speed was below 10 km h⁻¹ to ensure effective absorption. This timing was chosen to promote post-cutting branching while avoiding early floral inhibition reported with higher or mistimed GA₃ doses. A calibrated backpack sprayer (500–600 L ha⁻¹) was used for uniform application and untreated plots (0 ppm) were maintained as the control.

Top-cutting was strictly done at 30 DAT and plants were kept healthy with uniform fertilization and irrigation. Moderate GA₃ concentrations of 50–100 ppm were considered the likely optimum range, while excessive rates were avoided due to the risk of floral inhibition. Sprays were timed to coincide with early lateral growth at 7 and 14 DATC. Applications were not carried out during high temperature conditions above 34 °C or when rainfall was expected within 6 hours to ensure effective absorption and performance.

2.4 Sampling and measurements

2.4.1. Growth parameters

At the time of ultimate harvest (maturity), growth metrics were noted. A graduated scale was used to measure the plant's height (in centimeters) from the ground to the tip of the main stem. By counting every primary branch that emerged from the main stem, the number of branches per plant was ascertained. Five randomly chosen plants from each experimental unit were evaluated for these parameters, and the mean values were computed [2, 3].

2.4.2. Reproductive parameters

The same five randomly chosen plants from each plot were evaluated for reproductive factors at maturity. All completely formed pods were counted to calculate the number of pods per plant. Ten pods were chosen at random from each plant, threshed, and the number of seeds per pod was averaged. Using an electronic seed counter and a digital balance, 1000 seeds from each plot's bulk harvest were counted to determine the thousand-seed weight (g) [2]. In order to calculate seed yield (kg ha⁻¹), all pods from the net plot area (apart from boundary rows) were threshed, cleaned, weighed, and

converted to kilogram per hectare based on the harvested area [16].

2.4.3 Seed quality and seed health parameters

Standard laboratory techniques were used to assess seed quality characteristics. The between-paper (BP) method was used to assess the germination percentage (%) in a germination chamber at 25 ± 2°C with four replicates of 50 seeds each. Counts were made seven days after planting, and a seed was deemed germinated when the radicle reached 2 mm in length (ISTA, 2019). The following formula was used to determine the vigor index: (Seedling shoot length (cm) + root length (cm)) × Germination percentage (%) [1]. 50 pre-weighed seeds were soaked in 250 ml of deionized water at 25°C for 24 hours to measure the electrical conductivity (EC) of seed leachates (mS cm⁻¹). A calibrated EC meter was then used to record the conductivity of the solution; a lower EC indicates better membrane integrity [17]. In order to determine accelerated aging germination (%), seeds were exposed to 41°C and 100% relative humidity for 72 hours in an accelerated aging chamber. This was followed by a routine germination test to determine seed storability and stress resistance [9].

2.5 Statistical Analysis

The collected data were subjected to two-way analysis of variance (ANOVA) to evaluate the effects of variety, GA₃ concentration, and their interaction. Percentage data were transformed where necessary to meet the assumptions of normality and homogeneity of variance prior to analysis. Mean comparisons were performed using Tukey's Honestly Significant Difference (HSD) test at a 5% level of significance ($\alpha = 0.05$).

Pearson's correlation analysis was conducted to assess the relationships among seed yield, growth traits (plant height and branches per plant), yield components (pods per plant, seeds per pod, and thousand-seed weight), and seed quality parameters (germination percentage, vigor index, and electrical conductivity). Correlation coefficients (r) were used to quantify the strength and direction of relationships among variables using Statistix 8.1 software (Analytical Software, Tallahassee, FL, USA).

3. Results

The influence of different GA₃ concentrations on growth, yield and seed quality of two kenaf varieties (BJRI Kenaf 4 and BJRI Kenaf 5) was examined. Results revealed significant varietal and treatment effects with their interactions on plant growth traits, yield attributes and seed quality parameters.

3.1 Growth parameters

3.1.1 Effect of GA₃ on plant height

The effect of GA₃ treatments on plant height showed a significant increase up to 75 ppm, followed by a decline at higher concentrations. In BJRI Kenaf 4, the mean plant height increased from 190 cm in the control to 198 cm at 25 ppm, 214 cm at 50 ppm, and reached a maximum of 224 cm at 75 ppm.

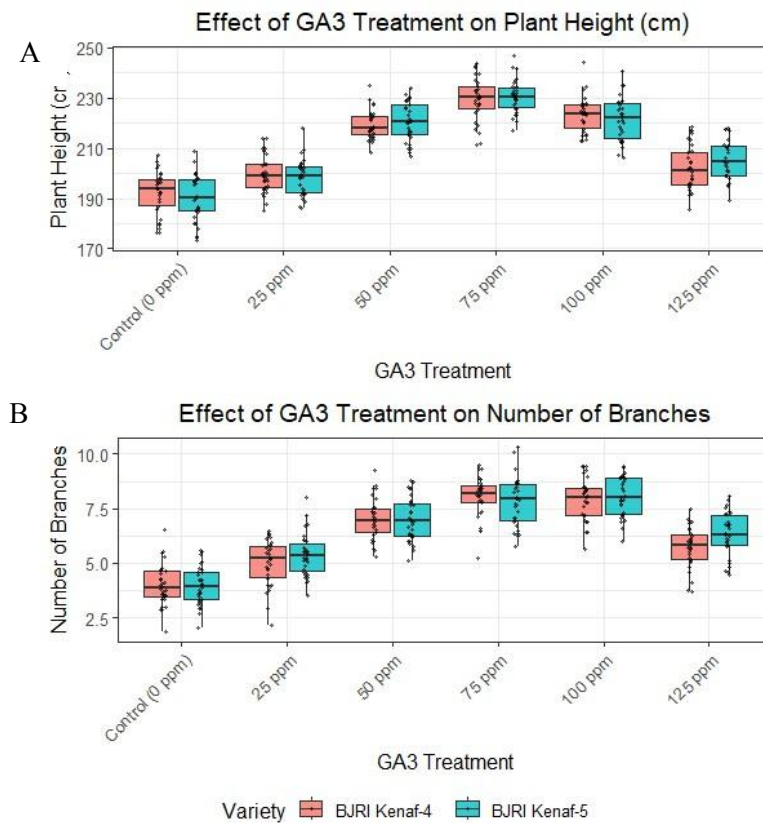


Figure 1. Effect of GA₃ on growth, reproductive yield and seed quality parameters such as- plant height (1A), number of branches (1B), pods per plants (1C), Seeds per pod (1D), thousands seed weight (1E), seed yield (1F), germination percentage (1G), vigors index (1H), EC level (1I) and AA germination (1J) of BJRI Kenaf 4 and BJRI Kenaf 5 via top cutting method.

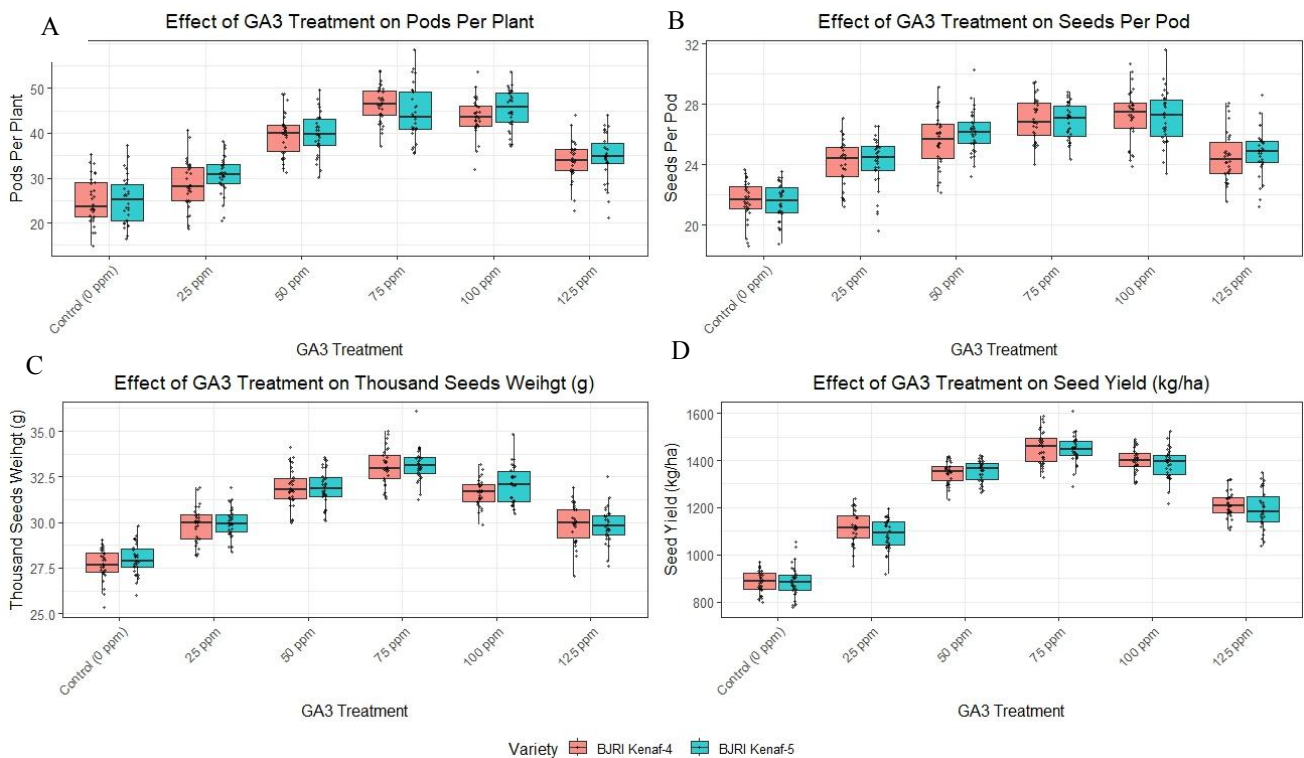


Figure 2. Effect of GA₃ on some reproductive growth factors such as number of pods per plant (A) , number of seeds per pod (B), thousands seed weight (C) and seeds yield (D) per hector related to enhance kenaf seed production at late season via top-cutting method for BJRI realeased varietis BJRI Kenaf 4 and BJRI Kenaf 5.

A similar trend was observed in BJRI Kenaf 5, where plant height increased from 192 cm in the control to 200 cm at 25 ppm, 216 cm at 50 ppm and peaked at 226 cm at 75 ppm. However, higher GA₃ levels resulted in reduced height, with BJRI Kenaf 4 and BJRI Kenaf 5 recording 216 cm and 218 cm at 100 ppm and further declining to 206 cm and 208 cm at 125 ppm, respectively (Figure 1A).

3.1.2 Effect of GA₃ on branches per plant

GA₃ application also significantly influenced the number of branches per plant, with maximum values recorded at 75–100 ppm. In BJRI Kenaf 4, the number of branches increased progressively from 4.3 in the control to 5.5 at 25 ppm, 6.9 at 50 ppm and peaked at 8.0 at 75 ppm. A further slight increase was observed at 100 ppm (8.2), before declining sharply to 6.0 at 125 ppm. A similar pattern was found in BJRI Kenaf 5, where branch number increased from 4.0 in the control to 5.3 at 25 ppm, 6.7 at 50 ppm, and reached the highest at 8.2 branches at 75 ppm. The value slightly decreased to 8.0 at 100 ppm and dropped to 6.2 at 125 ppm (Figure 1B).

3.2 Reproductive parameters

3.2.1 Effect of GA₃ on pods per plant

The number of pods per plant was significantly influenced by GA₃ application in both kenaf varieties. In BJRI Kenaf 4, pods per plant increased from 23 in the control to 50 at 75 ppm, before declining slightly to 47 at 100 ppm and 34 at 125 ppm. Similarly, BJRI Kenaf 5 showed a comparable trend, with pod numbers rising from 25 in the control to a maximum of 52 at 75 ppm and then decreased to 49 and 36 at 100 ppm and 125 ppm, respectively. These results suggest that moderate GA₃ doses (50–75 ppm) were most effective in enhancing pod formation (Figure 2A).

3.2.2 Effect of GA₃ on seeds per pod

Seeds per pod also varied with GA₃ treatment across both varieties. In BJRI Kenaf 4, seed number increased from 21 in the untreated control to 28 at 75 ppm, but declined to 27 and 25 at 100 ppm and 125 ppm, respectively. BJRI Kenaf 5 exhibited a similar pattern, produced 22 seeds per pod in the control, peaking at 29 seeds at 75 ppm and then slightly reduced to 28 and 26 at the two higher concentrations. The findings indicate that GA₃ application at 50–75 ppm enhanced seed set per pod in both varieties (Figure 2B).

3.2.3 Effect of GA₃ on thousand seed weight

Thousand seed weight showed notable improvements with GA₃ application. In BJRI Kenaf 4, weight increased from 27.5 g in the control to a maximum of 32 g at 75 ppm, before declining to 30 g and 29 g at 100 and 125 ppm, respectively. BJRI Kenaf 5 demonstrated similar increments, with thousand seed weight rising from 28 g in the control to 32.5 g at 75 ppm and then dropped to 30.5 g and 29.5 g at higher GA₃ doses. These results highlight that GA₃ treatments at moderate levels substantially improved seed size and weight (Figure 2C).

3.2.4 Effect of GA₃ on seed yield per plant

Seed yield was strongly affected by GA₃ treatment, with maximum yields obtained at intermediate doses. In BJRI Kenaf 4, yield increased from 850 kg ha⁻¹ in the control to a peak of 1450 kg ha⁻¹ at 75 ppm, then slightly decreased to 1400 kg ha⁻¹ and 1200 kg ha⁻¹ at 100 ppm and 125 ppm, respectively. In BJRI Kenaf 5, yield followed a similar trend, starting at 870 kg ha⁻¹ in the control, rising to 1470 kg ha⁻¹ at 75 ppm, and then declining to 1420 and 1220 kg ha⁻¹ at the higher doses. The data confirm that GA₃ application, particularly at 50–75 ppm, markedly enhanced seed yield potential in both varieties (Figure 1D).

3.3 Seed quality and seed health parameters

3.3.1 Effect of GA₃ on germination percentage

Germination percentage was markedly influenced by GA₃ treatments in both kenaf varieties. In BJRI Kenaf 4, germination increased from 75% in the untreated control to 85% at 25 ppm, and reached a maximum of 96% at 100 ppm before declining slightly to 92% at 125 ppm. Similarly, BJRI Kenaf 5 showed a comparable response, with germination improving from 77% in the control to 86% at 25 ppm, peaking at 97% at 100 ppm and then reducing slightly to 93% at the highest dose. These results indicate that GA₃ concentrations between 50–100 ppm enhanced germination capacity in both varieties (Figure 3A).

3.3.2 Effect of GA₃ on vigor index

Vigor index values exhibited a steady improvement with GA₃ treatment up to 100 ppm, after which a decline was observed. In BJRI Kenaf 4, the vigor index was 1500 in the control, which increased progressively to 1800 at 50 ppm and peaked at 2050 at 100 ppm, before declining to 1850 at 125 ppm. BJRI Kenaf 5 followed a similar trend, with vigor index values increasing from 1520 in the control to 1820 at 50 ppm and reaching a maximum of 2070 at 100 ppm, before dropping to 1870 at the highest GA₃ concentration (Figure 3B). This demonstrates that moderate GA₃ application substantially improved seedling vigor.

3.3.3 Effect of GA₃ on electrical conductivity (EC) of seed leachates

Electrical conductivity (EC), an indicator of membrane stability and seed quality, decreased with GA₃ application up to 75 ppm and increased thereafter. In BJRI Kenaf 4, EC values dropped from 48 mS cm⁻¹ in the control to a minimum of 28 mS cm⁻¹ at 75 ppm, before increasing to 36 mS cm⁻¹ at 125 ppm. Similarly, BJRI Kenaf 5 showed a reduction from 47 mS cm⁻¹ in the control to 27 mS cm⁻¹ at 75 ppm and then a slight rise to 35 mS cm⁻¹ at the highest GA₃ dose (Figure 3C). The results confirm that GA₃ treatments, particularly at 50–75 ppm, improved seed membrane integrity and reduced solute leakage.

3.3.4 Effect of GA₃ on accelerated aging germination

Accelerated aging germination improved considerably with GA₃ application, with the best performance observed between

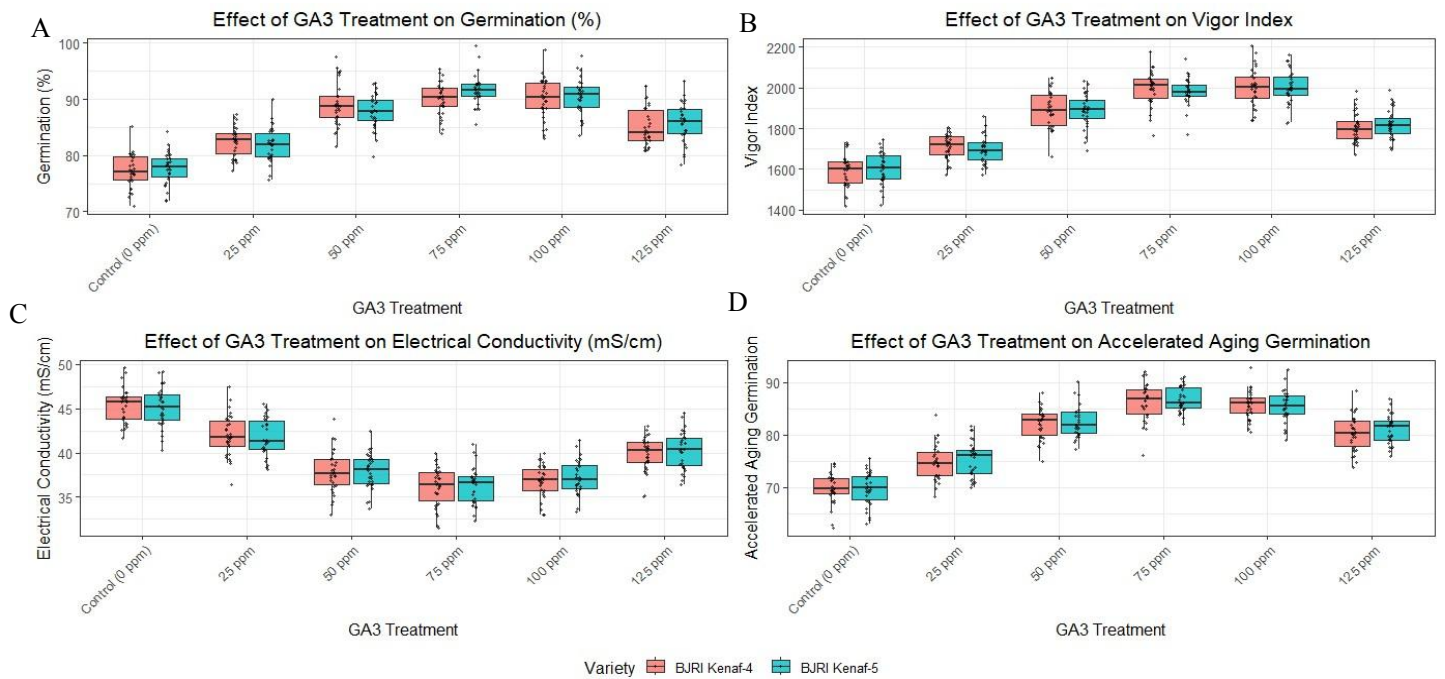


Figure 3. Effect of gibberellic acid (GA₃) treatments (0, 25, 50, 75, 100, and 125 ppm) on seed germination (%) (A), vigor index (B), electrical conductivity (mS cm⁻¹)(C) and accelerated aging germination (D) of two kenaf varieties (BJRI Kenaf 4 and BJRI Kenaf 5).

Table 1. Correlation coefficients among germination, vigor, seed yield, and yield-contributing traits in kenaf.

Traits	Germination (%)	EC	Vigor Index	Seed Yield	Thousand Seed Wt.	Seeds Pod ⁻¹	Pods Plant ⁻¹	Branches	Plant Height
Germination (%)	1.00	0.73	0.74	0.71	0.79	0.62	0.60	0.58	0.65
EC	0.73	1.00	0.70	0.69	0.72	0.59	0.65	0.55	0.63
Vigor Index	0.74	0.70	1.00	0.76	0.80	0.66	0.68	0.61	0.69
Seed Yield	0.71	0.69	0.76	1.00	0.82	0.70	0.75	0.67	0.87
Thousand Seed Wt.	0.79	0.72	0.80	0.82	1.00	0.73	0.72	0.63	0.74
Seeds Pod ⁻¹	0.62	0.59	0.66	0.70	0.73	1.00	0.64	0.56	0.61
Pods Plant ⁻¹	0.60	0.65	0.68	0.75	0.72	0.64	1.00	0.70	0.78
Branches	0.58	0.55	0.61	0.67	0.63	0.56	0.70	1.00	0.72
Plant Height	0.65	0.63	0.69	0.87	0.74	0.61	0.78	0.72	1.00

Note: EC = electrical conductivity. Values represent Pearson’s correlation coefficients (r).

50 and 75 ppm. In BJRI Kenaf 4, germination under accelerated aging conditions was 65% in the control, which increased to 85% at 50 ppm and peaked at 92% at 75 ppm, before declining to 83% at 125 ppm. BJRI Kenaf 5 followed a similar trend, increasing from 67% in the control to 86% at 50 ppm and reaching a maximum of 93% at 75 ppm, before reducing to 85% at the highest dose (Figure 3D). These findings highlight that GA₃ enhances seed storability and stress resilience at moderate concentrations.

3.4 Correlation Coefficients Among the Traits of Kenaf Varieties (BJRI Kenaf 4 and BJRI Kenaf 5)

The Pearson correlation matrix revealed strong positive associations among most of the measured traits (Table 1). Germination percentage showed significant positive correlations with EC ($r = 0.73$), vigor index ($r = 0.74$), seed yield ($r = 0.71$), and thousand-seed weight ($r = 0.79$), suggesting that improved germination contributes to enhanced plant establishment and yield components. EC was moderately correlated with pods per plant ($r = 0.65$) and plant height ($r = 0.63$), indicating a favorable association between electrical conductivity and vegetative growth. Vigor index displayed strong correlations with seed yield ($r =$

0.76) and thousand-seed weight ($r = 0.80$), confirming its role as a key indicator of productive potential. The highest correlation was observed between seed yield and plant height ($r = 0.87$), followed by seed yield and thousand-seed weight ($r = 0.82$). This indicates that taller plants and larger seeds contribute significantly to overall yield performance. Pods per plant also correlated well with plant height ($r = 0.78$), reflecting the additive contribution of reproductive traits to yield.

4. Discussion

The present investigation demonstrated that gibberellic acid (GA₃) application significantly enhanced growth, yield attributes and seed quality traits of both BJRI Kenaf 4 and BJRI Kenaf 5 varieties, with maximum improvements generally observed at moderate concentrations (50–75 ppm). These findings align with earlier reports indicating that exogenous GA₃ plays a pivotal role in stimulating stem elongation, cell division, and photosynthate partitioning toward reproductive structures, ultimately resulting in improved plant performance [5].

4.1 Growth parameters

Plant height and branching are primary indicators of vegetative vigor and canopy architecture in kenaf, directly influencing reproductive potential. In the present study, GA₃ significantly enhanced plant height and branch number, with optimal responses observed at 75 ppm, while higher concentrations resulted in a decline. This biphasic response can be attributed to the well-established role of GA₃ in promoting cell elongation, internodal expansion, and apical dominance release. Moderate levels likely stimulated axillary bud outgrowth following top-cutting [3], leading to improved canopy structure [2]. However, supra-optimal concentrations (≥ 100 ppm) may have disrupted endogenous hormonal balance, particularly the auxin–cytokinin–gibberellin interaction, resulting in reduced vegetative efficiency.

These findings are consistent with previous reports in kenaf and related crops, where optimal GA₃ doses enhanced plant height and branching, but excessive application led to diminished growth performance [6]. Similar hormetic responses have also been reported across crops, suggesting a broadly conserved physiological sensitivity to GA₃ across plant systems [13].

4.2 Reproductive traits and yield

Reproductive traits, including pods per plant, seeds per pod, thousand-seed weight, and overall seed yield, represent the cumulative outcome of assimilate partitioning and sink strength. In this study, these parameters were maximized at 50–75 ppm GA₃, with seed yield increasing by approximately 70% compared to the control. The enhancement in reproductive performance can be explained by improved source–sink dynamics, where GA₃ promotes photosynthetic activity and assimilate translocation toward developing reproductive organs [2, 7]. Additionally, GA₃ may enhance floral initiation, pollen viability, and fertilization efficiency,

leading to higher pod set and seed formation.

However, the decline at higher concentrations (125 ppm) suggests that excessive GA₃ may favor vegetative growth over reproductive allocation, thereby reducing effective sink development. This trade-off has been widely reported in crops such as sesame, cotton, and roselle, where optimal GA₃ levels improved yield attributes, while excessive doses reduced capsule or pod formation [15, 16, 18]. The consistency of these findings across species indicates that GA₃-mediated yield enhancement is concentration-dependent and closely linked to hormonal regulation of reproductive transitions.

4.3 Seed quality and vigor

Seed quality traits, including germination percentage, vigor index, electrical conductivity (EC), and accelerated aging performance, are critical indicators of seed physiological status and storability [19, 20]. In the present study, moderate GA₃ levels (50–100 ppm) significantly improved germination and vigor index, while EC values decreased, indicating enhanced membrane integrity. These improvements can be attributed to the role of GA₃ in activating hydrolytic enzymes (e.g., α -amylase), enhancing reserve mobilization, and promoting embryo growth during seed development [9]. Improved membrane stability, as reflected by lower EC, suggests reduced lipid peroxidation and better structural integrity of seed tissues [18]. The superior performance under accelerated aging further indicates that GA₃-treated seeds possess greater stress tolerance and longevity, likely due to improved biochemical composition and antioxidant capacity [21].

These findings align with earlier studies demonstrating that GA₃ enhances seed vigor and germination in kenaf and other crops through improved metabolic activity and membrane stability [8, 9]. Similar trends have also been reported in roselle and related Malvaceae species [1, 10].

4.4 Correlation Analysis and Breeding Implications

The correlation matrix revealed strong positive associations among germination percentage, vigor index, plant height, thousand-seed weight and seed yield. Particularly, the high correlation between plant height and seed yield ($r = 0.87$) and between thousand-seed weight and yield ($r = 0.82$) underscores the importance of these traits as indirect selection criteria in breeding programs. Similar positive correlations have been reported by Zhang et al. [9] and He et al. [22], reinforcing the reliability of these traits as predictors of yield potential. Breeding strategies that integrate selection for enhanced germination, seed weight and plant height could therefore simultaneously improve yield performance and seed quality in kenaf.

5. Conclusion

The present study demonstrated that foliar application of GA₃ significantly improved growth, yield and seed quality traits of kenaf (*H. cannabinus* L.) under top-cutting management. Among the tested concentrations, 50–75 ppm GA₃ consistently produced superior performance, resulting in taller

plants, more branches, higher pod and seed set, increased thousand-seed weight, and a substantial improvement in seed yield (up to 70% over control). Seed quality attributes including germination percentage, vigor index, and membrane stability were also maximized at moderate GA₃ concentrations, indicating enhanced physiological quality and storability. Correlation analysis confirmed that plant height, thousand-seed weight and vigor index are strongly and positively associated with seed yield, making them reliable indirect selection criteria for breeding and seed production programs. These findings suggest that judicious use of GA₃ at moderate doses can serve as a practical and cost-effective agronomic intervention to enhance kenaf seed production in Bangladesh and similar agro-ecological regions. Future research should focus on optimizing GA₃ application timing, exploring genotype-specific responses and integrating this approach with improved crop management practices for large-scale adoption.

Author contributions

Conceptualization, Arju Miah; Data curation, Arju Miah, Md Abdur Razzak Taohidi, Mohammad Shahadat Hossain, Md Kamrujjaman and Md Al-Mamun; Formal analysis, Md Abdur Razzak Taohidi, Marium Khatun, Md Siddikur Rahman; Funding acquisition, Arju Miah and Md Abdur Razzak Taohidi; Investigation, Arju Miah, Muhammad Iqbal Hossain; Writing— original draft, Arju Miah, Md Abdur Razzak Taohidi, Md. Mohshin Ali Mondol, Atik Hasan. All authors have read and agreed to the published version of the manuscript.

Ethical approval

Not applicable.

Conflicts of Interest

The authors report no conflicts of interest.

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Data availability statement

The data presented in this study are available on request from the corresponding author.

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