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On-field Runner Development in Strawberry with Gibberellic Acid under Sub-Tropical Terrace Soil Conditions

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ABSTRACT

Rapid multiplication of strawberry through runners is constrained in the acidic soils of tropical and subtropical regions, where short winters and irregular weather patterns prevail. In this context, plant growth regulators, particularly gibberellic acid (GA_3), can play a crucial role in promoting on-field runner development. Therefore, the present study aimed to determine an effective GA_3 application strategy for enhancing runner production in strawberry. GA_3 was applied at concentrations of 0.0 (control), 0.1, 0.5, and 1.0 millimolar (mM), with treatments administered either once or twice a week for one or two weeks, following a factorial randomized complete block design with three replications. Results indicated that GA_3 at 0.5 and 1.0 mM significantly increased the production of primary (3.88 runners plant^{-1}) and secondary (5.04 runners plant^{-1}) runners, respectively, compared to the control (1.43 and 1.62 runners plant^{-1}, respectively). Total runner counts were highest in plants treated with 1.0 mM GA_3 (8.60 runners plant^{-1}), followed by those treated with 0.5 mM (8.11 runners plant^{-1}). Interestingly, the frequency of GA_3 application had an inverse effect on runner production, with the highest runner numbers recorded under once-a-week spraying for one or two weeks (7.73 and 7.61 runners plant^{-1}, respectively), compared to twice-a-week spraying for two weeks (4.58 runners plant^{-1}). In the interaction effects, GA_3 at 1.0 mM applied once a week for one week exhibited a distinctive superiority, producing the highest number of runners (12.97 runners plant^{-1}), followed by 0.5 mM GA_3 applied once a week for two weeks (10.57 runners plant^{-1}). Based on these findings, a one-time foliar spray of GA_3 at 1.0 mM during the third week after transplanting is recommended for rapid runner production under challenging environmental conditions.

Introduction

Strawberry is a commercially important herbaceous fruit crop, valued for its high nutritional content, pleasant aroma, and attractive color. Although primarily a temperate crop, it is also cultivated in tropical and subtropical regions under intensive care and management (Oğuz et al., 2022; Gomasta et al., 2023; Nakayama and Nakazawa, 2023; Koly et al., 2024). The economic importance of strawberry is further reinforced by its propagation method, which relies predominantly on runner production. Runners, or stolons, are specialized long lateral stems developed from the parent crown that enable the vegetative propagation of strawberries (Megersa, 2017).

Clonal plants can also be generated via in vitro tissue culture of *Fragaria* × *ananassa* (Naing et al., 2019), utilizing plant growth regulators (PGRs), particularly through a carefully balanced ratio of auxins and

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cytokinins. However, this method is labor-intensive and costly, requiring skilled personnel, sophisticated equipment, and expensive materials (Sarker and Gomasta, 2024). Conversely, seed propagation is rarely practiced for commercial strawberry cultivation (Moieni et al., 2018). Thus, runner production remains the most effective method for ensuring rapid clonal multiplication and uniformity in commercial plantations.

Runner formation in strawberry is influenced by a range of factors, including environmental conditions, genetic background, and plant hormone regulation (Hytönen and Elomaa, 2011; Hytönen and Kurokura, 2020). Moreover, there exists a biological trade-off between flowering/fruiting and runner production. To facilitate propagation, this balance must be shifted toward vegetative runner formation (Gaston et al., 2021; Yang et al., 2024). Environmental factors such as temperature, photoperiod, and light intensity are crucial, as they regulate hormonal metabolism related to runner development (Hytönen et al., 2009). Runner emergence is severely limited under high temperatures and intense sunlight (Bradford et al., 2010), conditions commonly observed in the subtropics.

Accordingly, strawberry cultivation in the Bengal plains, characterized by a subtropical climate, has been standardized to the cooler months from November to February (Paul et al., 2017). Wang and Camp (2000) also suggested that an optimum day/night temperature of 25/12 °C is ideal for strawberry growth and development. However, regions near the equator and sub-equatorial zones rarely experience prolonged winters with such optimal temperatures (Khan et al., 2019). Consequently, short, dry winters and fluctuating temperatures in the tropics and subtropics present significant challenges to strawberry cultivation and multiplication (Gomasta et al., 2023).

Elevated temperatures can reduce the photosynthetic rate of strawberry plants by over 40% (Kadir et al., 2006) and disrupt the electron transport chain (Sage and Kubien, 2007). Furthermore, cultivated *Fragaria* × *ananassa* often produces runners sporadically, with considerable variation in growth and vigor across different varieties and locations (Hytönen and Elomaa, 2011), posing further challenges for consistent field-level propagation. Such physiological complexities often inhibit endogenous gibberellin (GA) biosynthesis, highlighting the potential of exogenous hormonal regulation as a practical approach.

Plant growth regulators (PGRs) have been widely recognized for their ability to modify the effects of environmental and genetic factors, stimulating plant growth and promoting runner development in strawberry (Sarker et al., 2020; Li et al., 2021). Several studies have demonstrated the effectiveness of PGRs and other external stimuli in optimizing runner production (Adak et al., 2009; Gambardella et al., 2016; Liu et al., 2019; Katel et al., 2022). However, most previous research has focused on strawberry regeneration under favorable or protected conditions. Therefore, technological interventions are necessary to ensure consistent and spontaneous runner production at the farmers' level under adverse tropical and subtropical climates. In this context, gibberellic acid (GA_3) application may enhance runner initiation even under suboptimal environmental conditions, thereby improving propagation efficiency. Accordingly, the present study was undertaken to maximize runner production in strawberry using GA_3 in terrace soil under a challenging subtropical ecosystem.

Material and methods

Experimental site: soil and weather

The research was conducted during the 2018–2019 and 2019–2020 growing seasons at the Fruit Research Farm of the Pomology Division, Bangladesh Agricultural Research Institute (BARI). Geographically, the field is located at 23°59'02.0" N latitude and 90°24'38.9" E longitude, with an elevation of approximately 8.4 meters above mean sea level. The soil belongs to the Chhiata series of the Madhupur Tract and is classified under the USDA Soil Taxonomy as Inceptisols (suborder: Aquepts; family: Grey Terrace Soils) (Huq and Shoaib, 2013). According to Mantel et al. (2023), the soil can also be classified as Gleyic Luvisols Cutanine and Gleyic Alisols Cutanine. Regarding climatic conditions, during the 2018–2019 season, daily maximum and minimum temperatures ranged from 36 °C in early October to 9 °C in early December. In the 2019–2020 season, temperatures ranged from 35 °C in early October to 10 °C in early February. Relative humidity (RH) fluctuated between 48% and 99% in 2018–2019 and between 49% and 96% in 2019–2020. Daily sunshine hours varied greatly in both seasons, ranging from completely overcast days with no sunshine to days with up to 10 hours of sunshine during the growing periods (Fig. 1).

Treatment materials and study design

The strawberry variety *BARI Strawberry-3*, a short-day cultivar released by the Bangladesh Agricultural Research Institute, was used as the planting material. Gibberellic acid (GA_3) (CAS No. 77-06-5, Cat. No. 00772, Research Lab, India) was employed as the treatment chemical. Factor A comprised four GA_3 concentrations: 0.0 mM (control), 0.1 mM, 0.5 mM, and 1.0 mM. Factor B consisted of four foliar application techniques: once a week for one week, once a week for two weeks, twice a week for one week, and twice a week for two weeks. The selection of doses and application methods was based on previous scholarly reports (Fagherazzi et al., 2017; Katel et al., 2022; Amin et al., 2023) as well as the authors’ own experiences (Sarker et al., 2020; Gomasta et al., 2024). The experiment was arranged in a randomized complete block design (RCBD) with three replications.

Crop cultivation and management

According to the experimental design, a total of forty-eight raised beds, each measuring 2.4 m × 1.2 m, were prepared across three separate blocks (16 beds per block, with each bed representing a replication). A distance of 100 cm was maintained between the blocks, while individual beds within each block were spaced 50 cm apart. Thirty-day-old strawberry saplings were transplanted on 12 October 2018 (first year) and 8 October 2019 (second year). Eight transplants were planted per bed in two rows, maintaining a spacing of 60 cm × 60 cm. All intercultural operations, including weeding, irrigation, fertilization, pest and disease management, and mulching, were carried out following approved guidelines (Azad et al., 2020). Runners and sub-runners were allowed to grow and were set in pots as soon as crown formation occurred. Subsequently, the potted runners were detached from the mother plants 25 days after emergence (Fig. 2).

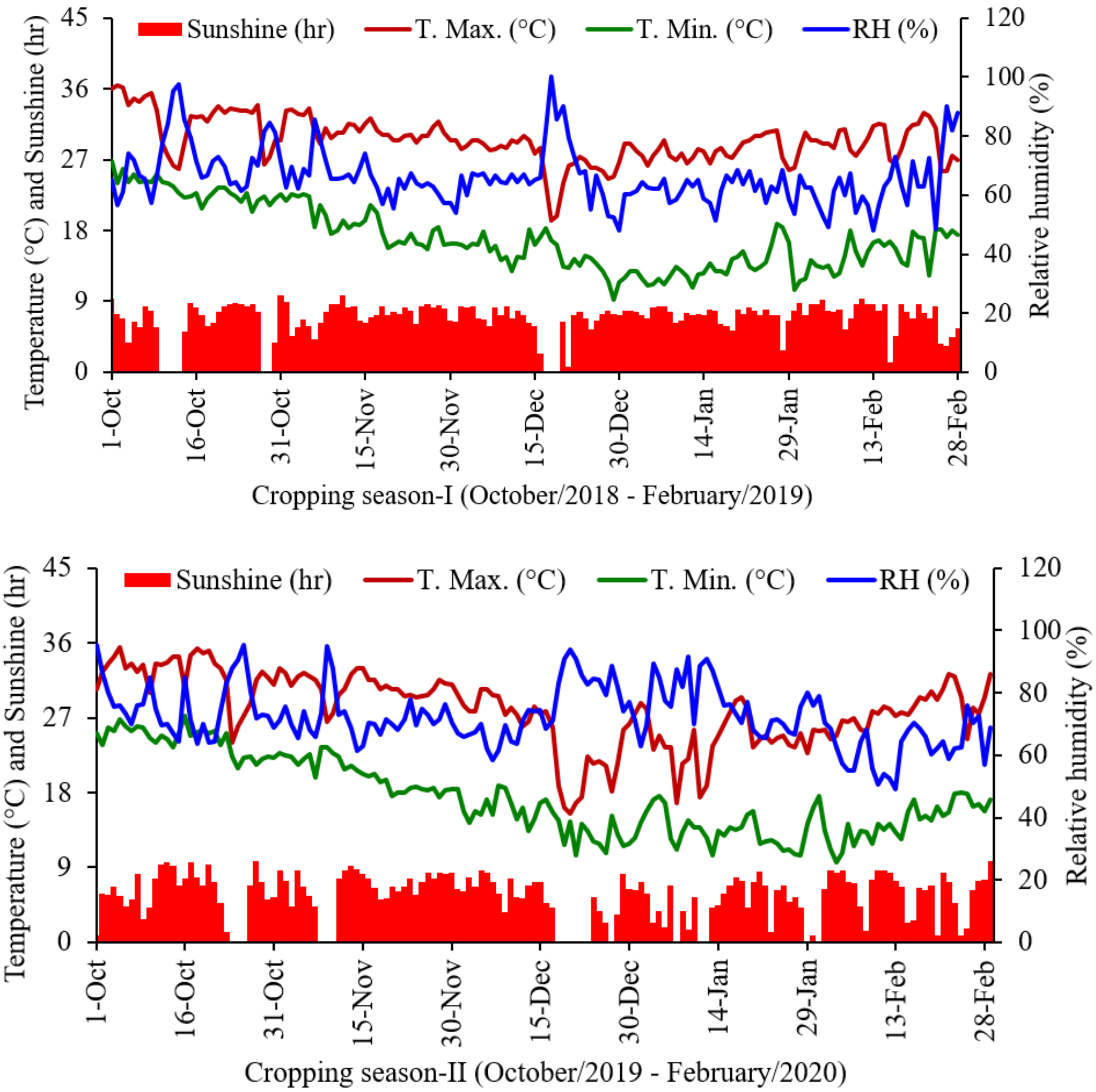

Fig. 1. Average of daily temperature (maximum and minimum), relative humidity and sunshine hour of the two consecutive cropping seasons at the experimental site. Here, T. Max.: Maximum temperature, T. Min.: Minimum temperature, and RH: Relative humidity.

Fig. 2. Schematic view of the experiment showing runner production in different treatments after gibberellic acid (GA_3) foliar spray. Here, (A) spraying GA_3 at the strawberry transplants, (B) runners started producing from the transplants, (C) the field with full of runners after treatment, (D) runners after treating with GA_3 at 1.0 mM at once a week for one week, (E) runners after treating with GA_3 at 0.5 mM at once a week for one week, and (F) runners after treating with GA_3 at 0.5 mM at twice a week for one week.

Treatment formulation and field application

Different concentrations of GA_3 were prepared on the day of application according to the schedule, following Uddin et al. (2024) with slight modifications. To prepare 1 L of 0.1 mM GA_3 solution, exactly 34.6 mg of GA_3 powder was first dissolved in 5 mL of 70% ethanol, then diluted to the 1 L mark with distilled water, along with the addition of 2–3 drops of Tween-20 (0.1%) as a surfactant. The same procedure was followed to prepare the 0.5 mM and 1.0 mM solutions, dissolving 173.2 mg and 346.4 mg of GA_3 powder, respectively. For the control treatment, 1 L of solution was prepared using 5 mL of ethanol and 2–3 drops of Tween-20, topped up with distilled water, without adding GA_3. The first foliar spray was applied 30 d after transplanting, once the plants were well established and capable of effectively absorbing external growth-promoting stimuli. Subsequent applications were carried out according to the experimental design. For treatments involving “once a week for two weeks” and “twice a week for two weeks,” sprays were applied over two consecutive weeks. Each spraying event targeted both sides of the leaves until runoff was observed. During each spray schedule, the eight transplants in a bed were treated with a total of 800 mL of solution, applying approximately 100 mL plant^{-1}.

Data collection

Runners started to develop from the crowns of the strawberry plants on 17 November 2018 (first year) and 16 November 2019 (second year). Primary runners, after travelling a certain distance, formed crowns. The crowns were put in a growth media on pots and allowed to develop secondary runners. The number of primary and secondary runners plant^{-1} was counted until the eighth week of runner production. Plant height and number of leaves plant^{-1} of the base plant were also recorded during the final observations in both seasons.

Statistical analysis

Initially, an F-test was conducted to assess the homogeneity of variances across the two years of data for all studied parameters. Upon confirmation of homogeneity, a combined analysis of variance (ANOVA) was carried out to test the treatment effects, following the procedures outlined by Gomez and Gomez (1984). Treatment means were compared using Fisher’s protected least significant difference (LSD) test at an appropriate significance level. Additionally, a correlation matrix was employed to evaluate the nature and strength of interrelationships among the traits in response to GA_3 treatments. All statistical analyses were performed using various packages within the R statistical software (version 4.1.2; R Core Team, 2020).

Results

The combined analysis of variance (Table 1) revealed that the two-way interactions between year (Y) and GA$_3$ dose (G), year and application technique (T), as well as the three-way interaction among year, GA$_3$ dose, and application technique (Y × G × T), had no significant effects on strawberry growth and runner production. Similarly, the main effect of year was non-significant for most of the studied parameters. In contrast, the main effects of GA$_3$ dose and application technique, along with their interaction (G × T), exhibited highly significant influences on growth and runner production traits of strawberry under the conditions of this study.

Table 1. Combined ANOVA for the effect of GA$_3$ application in various techniques on growth and runner of strawberry over two years.

Sources of variation	Degrees of freedom	Mean squares of various parameters				
		PHT	NLF	PRN	SRN	TRN
Replication × Year	4	3.30^{ns}	12.26*	0.24*	0.27^{ns}	0.90**
Year (Y)	1	17.68*	0.70^{ns}	0.62*	0.01^{ns}	0.75^{ns}
GA$_3$ dose (G)	3	479.65**	2551.68**	28.53**	51.74**	151.18**
Application technique (T)	3	80.97**	324.07**	2.07**	36.18**	51.42**
Y × G	3	2.01^{ns}	0.41^{ns}	0.04^{ns}	0.01^{ns}	0.09^{ns}
Y × T	3	0.80^{ns}	0.35^{ns}	0.01^{ns}	0.13^{ns}	0.11^{ns}
G × T	9	41.99**	125.02**	2.50**	12.86**	22.34**
Y × G × T	9	20.41**	12.03**	-6.10^{ns}	-5.80^{ns}	-5.25^{ns}
Error	60	3.97	3.50	0.10	0.12	0.20
Total	95					

Here, PHT, NLF, PRN, SRN and TRN indicate plant height, number of leaves plant^{-1}, and number of primary runners, secondary runners and total runners plant^{-1}; * and ** represent level of significance at 5 and 1% level of probability; ^{ns} correspond not-significant.

Effect of GA$_3$ doses on growth and runner production

Gibberellic acid (GA$_3$) significantly influenced all measured traits, including plant height, number of leaves per plant, and the number of primary and secondary runners per plant, compared to the control (Table 2). The highest plant height and number of leaves per plant were observed with GA$_3$ at 1.0 mM and 0.5 mM, whereas the control (0.0 mM) recorded the lowest values—14.98 cm in plant height and 18.18 leaves per plant. In terms of runner productivity, GA$_3$ at 0.5 mM produced the highest number of primary runners (3.88 plant^{-1}), followed by 1.0 mM (3.56 plant^{-1}), while the control yielded only 1.43 primary runners per plant. The number of secondary runners per plant peaked at 1.0 mM GA$_3$ (5.04), followed by 0.5 mM (4.23), both significantly higher than the control (1.62). Overall, the total number of runners was highest with 1.0 mM GA$_3$ (8.60 plant^{-1}), followed by 0.5 mM (8.11), whereas the control recorded the lowest runner production (3.05 plant^{-1}) (Table 2).

Effect of GA$_3$ application techniques on growth and runner production

Significant differences were observed among the GA$_3$ application methods with respect to plant growth and runner production traits (Table 3). The tallest plants (21.53 cm) were recorded under the treatment involving GA$_3$ application once a week for two weeks. The number of leaves per plant varied between 24.18 and 32.70 across different application frequencies. The highest number of primary runners (3.37 plant^{-1}) was also obtained with the once-a-week-for-two-weeks application, followed by the once-a-week-for-one-week treatment (3.12 plant^{-1}). The lowest number of primary runners (2.74 plant^{-1}) was produced by the twice-a-week-for-two-weeks method, which was statistically similar to the twice-a-week-for-one-week treatment (2.79 plant^{-1}). For secondary runner production, spraying GA$_3$ once a week for one week yielded the highest number (4.61 plant^{-1}), followed by the once-a-week-for-two-weeks method (4.24 plant^{-1}). The lowest number of secondary runners was observed with the twice-a-week-for-two-weeks treatment (1.84 plant^{-1}), followed by the twice-a-week-for-one-week application (3.53 plant^{-1}). Overall, the total number of runners was significantly highest (7.73 plant^{-1}) in the once-a-week-for-one-week treatment, which was statistically at par with the once-a-week-for-two-weeks method (7.61 plant^{-1}). In contrast, the twice-a-week-for-two-weeks application resulted in the lowest total runner production (4.58 plant^{-1}) (Table 3).

Table 2. Main effect of GA$_3$ doses on growth and runner production of strawberry var. *BARI Strawberry-2.*

GA$_3$ doses	Plant height (cm)	Number of leaves plant^{-1}	Number of primary runners plant^{-1}	Number of secondary runners plant^{-1}	Total number of runners plant^{-1}
GA$_3$ at 1.0 mM	24.08±1.35^{a}	31.75±1.15^{b}	3.56±0.13^{b}	5.04±0.27^{a}	8.60±0.25^{a}
GA$_3$ at 0.5 mM	23.05±1.05^{a}	40.83±1.25^{a}	3.88±0.19^{a}	4.23±0.17^{b}	8.11±0.33^{b}
GA$_3$ at 0.1 mM	17.00±0.98^{b}	21.38±1.01^{c}	3.14±0.16^{c}	3.34±0.17^{c}	6.48±0.27^{c}
GA$_3$ at 0.0 mM	14.98±0.99^{c}	18.18±0.49^{d}	1.43±0.15^{d}	1.62±0.17^{d}	3.05±0.17^{d}
Level of significance	**	**	**	**	**
CV (%)	9.91	6.15	9.03	9.70	6.62

Different letters within the column indicate statistically significant differences among the treatments according to LSD at $p < 0.05$. **: Significant at 1% level of probability.

Table 3. Main effect of GA$_3$ application techniques on growth and runner production of strawberry var. *BARI Strawberry-2.*

Application techniques	Plant height (cm)	Number of leaves plant^{-1}	Number of primary runners plant^{-1}	Number of secondary runners plant^{-1}	Total number of runners plant^{-1}
Once a week for one week	17.25±0.97^{c}	32.70±1.01^{a}	3.12±0.19^{b}	4.61±0.16^{a}	7.73±0.27^{a}
Once a week for two weeks	21.53±1.10^{a}	26.30±0.87^{c}	3.37±0.16^{a}	4.24±0.25^{b}	7.61±0.30^{a}
Twice a week for one week	20.60±1.21^{ab}	28.95±1.09^{b}	2.79±0.15^{c}	3.53±0.19^{c}	6.33±0.28^{b}
Twice a week for two weeks	19.73±1.10^{b}	24.18±0.94^{d}	2.74±0.13^{d}	1.84±0.18^{d}	4.58±0.20^{c}
Level of significance	**	**	**	**	**
CV (%)	9.91	6.15	9.03	9.70	6.62

Different letters within the column indicate statistically significant differences among the treatments according to LSD at $p < 0.05$. **: Significant at 1% level of probability.

Interaction effect of GA$_3$ doses and application techniques

Plant height, number of leaves per plant, and the number of primary and secondary runners per plant were significantly influenced by the interaction between GA$_3$ concentration and application frequency (Table 4). The tallest plants (27.60 cm) were recorded under the treatment of 1.0 mM GA$_3$ applied twice a week for one week, whereas the shortest plants (14.38 cm) were observed in the control (0.0 mM GA$_3$) under the twice-a-week-for-two-weeks regimen. The highest number of leaves per plant (46.30) was observed in plants treated with 0.5 mM GA$_3$ applied twice a week for one week, followed by 1.0 mM GA$_3$ applied once a week for one week (40.80), and 0.5 mM GA$_3$ applied once a week for one week (43.00). The lowest number of leaves (15.50 per plant) was recorded in plants treated with 0.1 mM GA$_3$ applied once a week for two weeks, which was statistically similar to the control treatments under once-a-week-for-two-weeks and twice-a-week-for-one-week application methods. In terms of primary runner production, the highest number (4.83 per plant) was recorded in the 0.5 mM GA$_3$ treatment applied once a week for two weeks, followed by 1.0 mM GA$_3$ applied once a week for one week (4.43), and 0.5 mM GA$_3$ under the same frequency (4.20). The highest number of secondary runners (8.53 per plant) was found in plants treated with 1.0 mM GA$_3$ applied once a week for one week, followed by 1.0 mM GA$_3$ applied once a week for two weeks (5.30), 0.5 mM GA$_3$ applied once a week for two weeks (5.73), and 0.5 mM GA$_3$ applied twice a week for one week (5.20). Consequently, the maximum total number of runners (12.97 per plant) was achieved with 1.0 mM GA$_3$ applied once a week for one week, followed by 0.5 mM GA$_3$ applied once a week for two weeks (10.57). In contrast, all application schedules under the control treatment (0.0 mM GA$_3$) resulted in the lowest runner production, indicating minimal response in the absence of exogenous GA$_3$ (Table 4).

Table 4. Interaction effect of GA_3 doses and application techniques on growth and runner production in strawberry var. *BARI Strawberry-2.*

GA_3 doses	Application techniques	Plant height (cm)	Number of leaves plant^{-1}	Number of primary runners plant^{-1}	Number of secondary runners plant^{-1}	Total number of runners plant^{-1}
GA_3 at 1.0 mM	Once a week for one week	$22.50 \pm 1.21^{c-e}$	40.80 ± 1.21^{b}	4.43 ± 0.20^{ab}	8.53 ± 0.32^{a}	12.97 ± 0.12^{a}
	Once a week for two weeks	$25.40 \pm 1.19^{a-c}$	34.50 ± 1.61^{c}	3.87 ± 0.15^{cd}	5.30 ± 0.29^{bc}	9.17 ± 0.37^{c}
	Twice a week for one week	27.60 ± 1.56^{a}	30.00 ± 0.99^{d}	2.97 ± 0.12^{e}	4.93 ± 0.29^{cd}	7.90 ± 0.40^{d}
	Twice a week for two weeks	20.80 ± 1.45^{ef}	21.70 ± 0.79^{ef}	2.97 ± 0.07^{e}	1.40 ± 0.17^{g}	4.37 ± 0.12^{f}
GA_3 at 0.5 mM	Once a week for one week	17.40 ± 0.78^{gh}	43.00 ± 0.83^{b}	4.20 ± 0.17^{bc}	4.17 ± 0.12^{e}	8.37 ± 0.29^{cd}
	Once a week for two weeks	$24.20 \pm 1.01^{b-d}$	37.30 ± 0.71^{c}	4.83 ± 0.20^{a}	5.73 ± 0.26^{b}	10.57 ± 0.46^{b}
	Twice a week for one week	$24.70 \pm 1.13^{a-c}$	46.30 ± 1.79^{a}	3.57 ± 0.23^{d}	5.20 ± 0.12^{bc}	8.77 ± 0.32^{c}
	Twice a week for two weeks	25.90 ± 1.30^{ab}	36.70 ± 1.68^{c}	2.93 ± 0.15^{e}	1.80 ± 0.17^{g}	4.73 ± 0.27^{f}
GA_3 at 0.1 mM	Once a week for one week	14.60 ± 0.69^{gh}	28.50 ± 1.70^{d}	2.30 ± 0.15^{f}	3.90 ± 0.12^{e}	6.20 ± 0.26^{e}
	Once a week for two weeks	21.20 ± 1.10^{de}	15.50 ± 0.55^{h}	3.60 ± 0.17^{d}	4.37 ± 0.23^{de}	7.97 ± 0.23^{d}
	Twice a week for one week	14.40 ± 1.01^{h}	22.20 ± 1.18^{e}	3.10 ± 0.17^{e}	2.47 ± 0.20^{f}	5.57 ± 0.32^{e}
	Twice a week for two weeks	17.80 ± 1.13^{fg}	19.30 ± 0.61^{fg}	3.57 ± 0.15^{d}	2.63 ± 0.15^{f}	6.20 ± 0.25^{e}
GA_3 at 0.0 mM (control)	Once a week for one week	14.50 ± 1.21^{h}	18.50 ± 0.29^{g}	1.53 ± 0.22^{g}	1.83 ± 0.09^{g}	3.37 ± 0.28^{g}
	Once a week for two weeks	15.30 ± 1.10^{gh}	17.90 ± 0.61^{gh}	1.17 ± 0.12^{g}	1.57 ± 0.20^{g}	2.73 ± 0.13^{g}
	Twice a week for one week	15.70 ± 1.13^{gh}	17.30 ± 0.40^{gh}	1.53 ± 0.09^{g}	1.53 ± 0.13^{g}	3.07 ± 0.09^{g}
	Twice a week for two weeks	14.38 ± 0.52^{h}	19.00 ± 0.67^{fg}	1.50 ± 0.17^{g}	1.53 ± 0.24^{g}	3.03 ± 0.17^{g}
Level of significance		**	**	**	**	**
CV (%)		9.91	6.15	9.03	9.70	6.62

Different letters within the column indicate statistically significant differences among the treatments according to LSD at $p < 0.05$. **: Significant at 1% level of probability.

Correlation analysis

Pearson's correlation coefficient analysis revealed moderate to very strong positive relationships ($0.54 \leq r \leq 0.97$) among the plant growth and runner development traits in strawberry following GA_3 application at different concentrations and frequencies (Fig. 3). Plant height (PHT) and number of leaves per plant (NLF) both increased in response to GA_3 treatments and showed a moderate correlation with each other ($r \geq 0.54$). Plant height also exhibited moderate positive correlations with the number of primary runners (PRN, $r \geq 0.52$), secondary runners (SRN, $r \geq 0.57$), and total runners per plant (TRN, $r \geq 0.60$). Stronger correlations were observed between NLF and PRN ($r \geq 0.64$), SRN ($r \geq 0.66$), and TRN ($r \geq 0.70$), suggesting that an increase in leaf number due to GA_3 application substantially enhanced runner formation. A strong correlation between PRN and SRN ($r \geq 0.73$), and very strong correlations between TRN and both PRN ($r \geq 0.88$) and SRN ($r \geq 0.97$), indicate that the cumulative increase in primary and secondary runners significantly contributed to the total runner production in GA_3-treated strawberry plants under the current experimental conditions (Fig. 3).

Discussion

Gibberellins are versatile plant growth regulators widely used to enhance vegetative growth, stress tolerance, yield, and produce quality in various crops. In the present study, gibberellic acid (GA_3) at low concentrations was applied to strawberry plants, and the results showed that GA_3 treatments produced distinct and significantly enhanced responses compared to the control (Tables 2, 3, and 4; Fig. 3). Notably, GA_3 application substantially increased runner production under ambient field conditions. As an endogenous tetracyclic diterpenoid hormone, GA_3

regulates numerous growth and developmental processes in plants (Shah et al., 2023). Its exogenous application helps stabilize internal hormonal balance at the cellular level, thereby promoting plant development even under suboptimal environmental conditions (Paroussi et al., 2002; Gomasta et al., 2024).

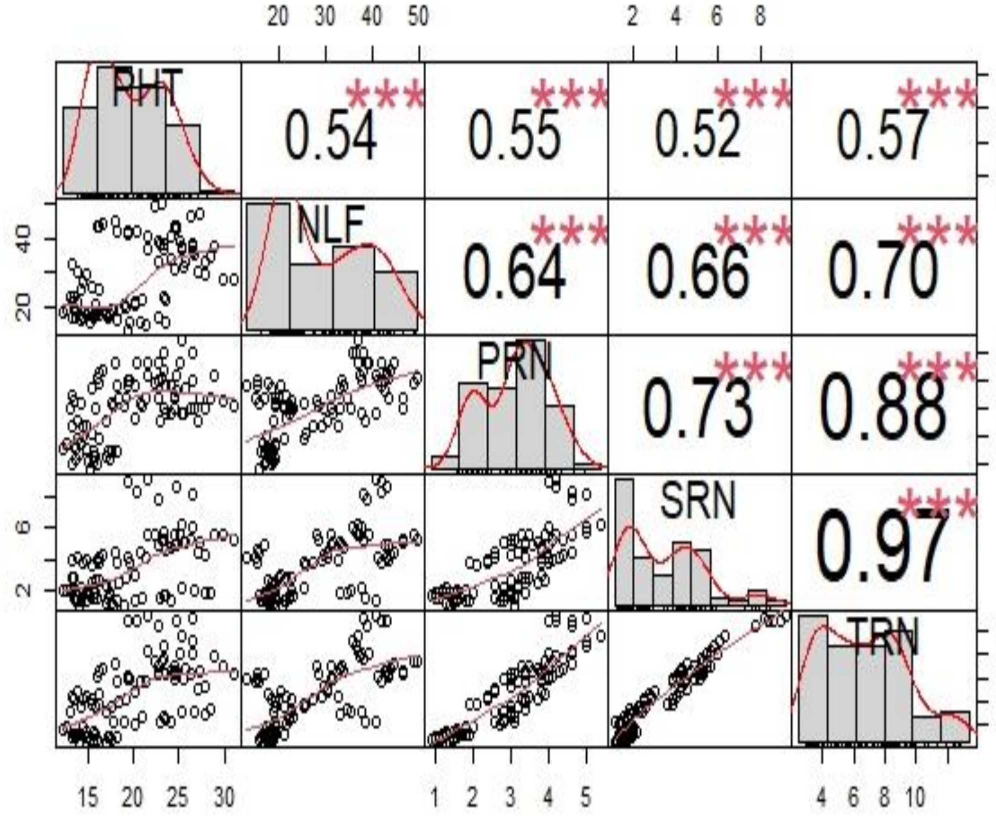

Fig. 3. Correlation matrix showing the relationship among the variables after treatment application. Here, PHT, NLF, PRN, SRN and TRN indicate plant height (cm), leaf number, primary runners, secondary runners and total number of runners plant^{-1}.

This role of GA_3 aligns with the current findings, as strawberry transplants grown under fluctuating sub-tropical conditions, characterized by variable temperature, humidity, and sunshine (Fig. 1), responded positively to GA_3. Higher concentrations, particularly 0.5 mM and 1.0 mM, led to enhanced vegetative growth and significantly higher runner production compared to lower concentration (0.1 mM) and the control (Tables 2 and 4). The combined analysis of variance further indicated that the year-to-year variation had no significant effect on runner productivity, suggesting that differences in runner output were solely attributable to GA_3 dose and application method. This consistency across both years supports the reliability and sustainability of the GA_3 application strategy employed (Table 1).

Regression analysis confirmed that increasing GA_3 concentration from 0.0 mM to 1.0 mM corresponded with a steady improvement in overall runner productivity, with near-maximum efficacy observed at 1.0 mM (Fig. 3). Since runner production in strawberry is a photoperiod-regulated, hormone-dependent process, the results highlight a strong endogenous control of this trait mediated by exogenous GA_3 application (Hytönen and Kurokura, 2020; Sarker et al., 2020). Hytönen et al. (2009) previously reported that, under long-day conditions with variable temperatures, endogenous prohexadione-calcium can suppress GA biosynthesis, limiting runner formation. A similar limitation was observed in the control treatment of this study. However, exogenous GA_3 application at appropriate concentrations effectively overcame this suppression and significantly promoted runnering, particularly at 0.5 mM and 1.0 mM GA_3. These findings are consistent with previous studies, where Kumar et al. (2019) reported enhanced vegetative growth and runner production with 250 ppm GA_3, and Amin et al. (2023) observed a substantial increase in runner counts at 450 ppm GA_3.

Moreover, vigorous shoot and leaf growth resulting from GA_3 application contributed to increased photoassimilate accumulation, thereby enhancing runner production in strawberry plants (Fig. 4). At the cellular level, gibberellic acid has been shown to stimulate cell division, elongation, and enlargement

(De Lucas et al., 2008). Additionally, GA_3 plays a critical role in regulating nitrogen metabolism and carbohydrate translocation, facilitating enhanced shoot and leaf development across several crops, including strawberry (Csukasi et al., 2011). These mechanisms are corroborated by earlier findings, where Paroussi et al. (2002), Kumra et al. (2018), Rathod et al. (2021), and Zhang et al. (2022) reported that GA_3 application promoted vegetative growth, stimulated runner production, elongated internodes, and induced stolon formation in strawberries.

Furthermore, transcriptomic analysis by Li et al. (2021) provided molecular insight into GA_3-induced runner development. RNA-Seq profiling revealed that several genes involved in hormone biosynthesis, metabolism, and signal transduction were significantly up- or down-regulated following GA_3 treatment at concentrations of 50–100 mg L^{-1}, suggesting that GA_3 modulates complex regulatory networks responsible for runner formation. In the present study, GA_3 at 1.0 mM applied once a week for one week resulted in over three times more runners (12.97) than the same dose applied twice a week for two weeks (4.37), indicating the importance of optimized application frequency (Table 4 and Fig. 2). Interestingly, at lower concentrations (0.1 and 0.5 mM), more runners were produced when GA_3 was applied once a week for two weeks rather than for just one week, highlighting the nuanced dose–response relationship of plant growth regulators. As a class of compounds active at minute concentrations, plant growth regulators like GA_3 exert profound effects on physiological and metabolic processes when applied at precise developmental stages (Sabagh et al., 2021). Gibberellic acid, in particular, is known for its complex interactions with environmental cues and internal signaling pathways, making it a powerful yet context-dependent growth stimulant (Gupta and Chakrabarty, 2013). Supporting this view, Roopendra et al. (2018) and Katel et al. (2022) demonstrated that timely GA_3 application at suitable doses enhances phloem loading, improves carbohydrate metabolism, increases photosynthetic assimilation, and promotes the formation of multiple stems—culminating in greater runner production in strawberry.

Consistent with the present findings, Pérez de Camacaro et al. (2009) reported that a single GA_3 spray at 20–40 mg L^{-1} increased stolon formation compared to untreated controls. Similarly, Sharma and Singh (2009) found that GA_3 application during November, February, or both, enhanced vegetative growth and runner emergence. Although Fagherazzi et al. (2017) did not observe a statistically significant increase in runner count following GA_3 treatment. They acknowledged that foliar spraying with higher concentrations did alter vegetative traits and contributed to runner development. In another study, Rathod et al. (2021) reported that GA_3 application at 30 and 60 d after transplanting led to superior root and shoot growth, ultimately supporting greater runner emergence.

Moreover, Hytönen et al. (2009) highlighted the photoperiodic regulation of axillary bud differentiation, either into long shoots (runners) under long days or crown branches under short days, and emphasized gibberellin’s pivotal role in mediating meristematic fate in both conditions. Altogether, the evidence underscored that exogenous application of gibberellic acid at appropriate concentrations and timings is crucial for optimizing vegetative growth and runner formation in strawberries, particularly under variable environmental conditions typical of tropical and subtropical climates.

Conclusions

Large-scale commercial cultivation of nutrient- and antioxidant-rich strawberries depends on the availability of healthy and uniform planting material. However, short winter durations and suboptimal soil conditions in tropical and subtropical regions can adversely affect rapid runner production. The present study demonstrated that a single application of gibberellic acid (GA_3) at 1.0 mM during the third week after transplanting, or two applications of 0.5 mM GA_3 during the third and fourth weeks, significantly enhanced the production of primary, secondary, and total runners. These findings suggest that growers in similar agroecological zones can adopt these GA_3 application strategies to improve on-field runner multiplication. Nonetheless, given that this experiment was conducted under specific subtropical conditions, caution must be exercised in generalizing the results. Further research is warranted to evaluate the long-term physiological effects of GA_3 on strawberry plants and to assess its efficacy across different strawberry cultivars, soil types, and climatic regions.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of Interest

The authors indicate no conflict of interest in this work.

References

Adak N, Kaynak L, Pekmezci M, Gubbuk H. 2009. The effect of various hormone types on in vitro propagation of strawberry. Acta Horticulturae 829, 305-308. https://doi.org/10.17660/ActaHortic.2009.829.46

Amin B, Qureshi KM, Ghani A, Mahmood A, Shah

SAS, Khan MF, Anwar I. 2023. Effect of different environments and GA_3 on growth and runners production of strawberry (*Frageria Ananasa*). Journal of Pharmaceutical Negative Results 208-218. https://doi.org/10.47750/pnr.2023.14.04.28

Azad AK, Miaruddin M, Wohab M A, Sheikh MHR, Nag BL, Rahman MHH (Eds.). 2020. Handbook on Agro-Technology. Bangladesh Agricultural Research Institute. Gazipur, Bangladesh. [in Bengali]

Bradford E, Hancock JF, Warner RM. 2010. Interactions of temperature and photoperiod determine expression of repeat flowering in strawberry. Journal of the American Society for Horticultural Science 135(2), 102-107. https://doi.org/10.21273/JASHS.135.2.102

Csukasi F, Osorio S, Gutierrez JR, Kitamura J, Giavalisco P, Nakajima M, Medina-Escobar N. 2011. Gibberellin biosynthesis and signalling during development of the strawberry receptacle. New Phytologist 191(2), 376-390. https://doi.org/10.1111/j.1469-8137.2011.03700.x

De Lucas M, Daviere JM, Rodríguez-Falcón M, Pontin M, Iglesias-Pedraz JM, Lorrain S, Prat S. 2008. A molecular framework for light and gibberellin control of cell elongation. Nature 451(7177), 480-484. https://doi.org/10.1038/nature06520

Fagherazzi AF, Grimaldi F, Kretzschmar AA, Rufato L, Lucchi P, Maltoni ML, Baruzzi G. 2017. Effects of GA_3 on vegetative growth in strawberry. Acta Horticulturae, (1156), 497-500. https://doi.org/10.17660/ActaHortic.2017.1156.73

Gambardella M, Massetani F, Neri D. 2016. Plant propagation techniques and types of plants. In Strawberry: growth, development and diseases (139-156). Wallingford UK: CABI. https://doi.org/10.1079/9781780646633.0139

Gaston A, Potier A, Alonso M Sabbadini S, Delmas F, Tenreira T, Denoyes B. 2021. The FveFT2 florigen/FveTFL1 antiflorigen balance is critical for the control of seasonal flowering in strawberry while FveFT3 modulates axillary meristem fate and yield. New Phytologist 232(1), 372-387. https://doi.org/10.1111/nph.17557

Gomasta J, Hassan J, Sultana H, Kayesh E. 2024. Interactive plant growth regulator and fertilizer application dataset on growth and yield attributes of tomato (Solanum lycopersicum L.). Data in Brief 57, 111136. https://doi.org/10.1016/j.dib.2024.111136

Gomasta J, Islam MR, Rahman MA, Islam M, Mondal P, Hassan J, Kayesh E. 2023. Watermoss mulching stimulates the productivity and physiochemical properties of strawberry in the tropical ecosystem of southern Bangladesh. Pertanika Journal of Tropical Agricultural Science 46(4), 1293-1308. https://doi.org/10.47836/pjtas.46.4.14

Gomez KA, Gomez AA. 1984. Statistical procedures for agricultural research. John Wiley & Sons.

Gupta R, Chakrabarty SK. 2013. Gibberellic acid in plant: still a mystery unresolved. Plant Signaling & Behavior 8(9), e25504. https://doi.org/10.4161/psb.25504

Huq SI, Shoaib JM. 2013. The soils of Bangladesh (Vol. 1). Dordrecht: Springer.

Hytönen T, Elomaa P, Moritz T, Junttila O. 2009. Gibberellin mediates daylength-controlled differentiation of vegetative meristems in strawberry (*Fragaria* × *ananassa* Duch). BMC Plant Biology 9, 1-12. https://doi.org/10.1186/1471-2229-9-18

Hytönen T, Elomaa P. 2011. Genetic and environmental regulation of flowering and runnering in strawberry. Genes, Genomes and Genomics 5, 56-64.

Hytönen T, Kurokura T. 2020. Control of flowering and runnering in strawberry. The Horticulture Journal 89(2), 96-107. https://doi.org/10.2503/hortj.UTD-R011

Kadir S, Sidhu G, Al-Khatib K. 2006. Strawberry (*Fragaria* × *ananassa* Duch.) growth and productivity as affected by temperature. HortScience 41(6), 1423-1430. https://doi.org/10.21273/HORTSCI.41.6.1423

Katel S, Mandal HR, Kattel S, Yadav SPS, Lamshal BS. 2022. Impacts of plant growth regulators in strawberry plant: A review. Heliyon 8(12). https://doi.org/10.1016/j.heliyon.2022.e11959

Khan MHR, Rahman A, Luo C, Kumar S, Islam GA, Hossain MA. 2019. Detection of changes and trends in climatic variables in Bangladesh during 1988-2017. Heliyon 5(3), e01268. https://doi.org/10.1016/j.heliyon.2019.e01268

Koly KA, Gomasta J, Kabir K, Mallick SR, Sultana H, Kayesh E. 2024. Yield and quality promotion of strawberries through chitosan and potassium combined spray under fluctuating sub-tropical winter. Journal of Central European Agriculture 25(4), 1065-1075. https://doi.org/10.5513/JCEA01/25.4.4228

Kumar V, Sahay S, Mir H, Ahmad F, Rashmi K. 2019. Effectiveness of plant growth regulators on vegetative growth of strawberry cv. Camarosa. International Journal of Current Microbiology and Applied Sciences 8(7), 1259-1264. https://doi.org/10.20546/ijcmas.2019.807.149

Kumra R, Saravanan RS, Bakshi P, Kumar A, Singh M, Kumar V. 2018. Influence of plant growth regulators on strawberry: A review. International Journal of Chemical Studies 6(1), 1236-1239.

Li W, Wang B, Sun H, Zhang Z. 2021. Transcriptome profiling of runner formation induced by exogenous gibberellin in *Fragaria vesca*. Scientia Horticulturae 281, 109966. https://doi.org/10.1016/j.scienta.2021.109966

Liu C, Guo Z, Park YG, Wei H, Jeong BR. 2019. PGR and its application method affect number and length of runners produced in ‘Maehyang’ and ‘Sulhyang’ strawberries. Agronomy 9(2), 59. https://doi.org/10.3390/agronomy9020059

Mantel S, Dondeyne S, Deckers S. 2023. World reference base for soil resources (WRB). Goss, Margaret Oliver Encyclopedia of Soils in the Environment, 2nd ed.; Michael, J., Ed, 206-217. https://doi.org/10.1016/B978-0-12-822974-3.00161-0

Megersa, H. G. (2017). Propagation methods of selected horticultural crops by specialized organs: review. Journal of Horticulture 4(198) 2376-0354. https://doi.org/10.4172/2376-0354.1000198

Moieni A, Tavizi A, Javaran MJ, Mohebodini M, Eskandari MH, Ebrahimie E. 2018. In Vitro Regeneration of Seven Strawberry (*Fragaria* × *ananassa* Duch.) Genotypes from Seed, Terminal Meristem, Terminal Bud, Leaf and Petiole Explants. Research & Reviews: Journal of Botanical Sciences 7(3), 1-8

Naing AH, Kim SH, Chung MY, Park SK, Kim CK. 2019. In vitro propagation method for production of morphologically and genetically stable plants of different strawberry cultivars. Plant Methods 15, 1-10. https://doi.org/10.1186/s13007-019-0421-0

Nakayama M, Nakazawa Y. 2023. Effects of environmental control and LED supplemental lighting on strawberry growth and yield in a subtropical climate. Scientia Horticulturae 321, 112349. https://doi.org/10.1016/j.scienta.2023.112349

Oğuz İ, Oğuz Hİ, Kafkas NE. 2022. Strawberry cultivation techniques. In Recent Studies on Strawberries. IntechOpen. https://doi.org/10.5772/intechopen.104611

Paroussi G, Voyiatzis DG, Paroussis E, Drogoudi PD. 2002. Growth, flowering and yield responses to GA_3 of strawberry grown under different environmental conditions. Scientia Horticulturae 96(1-4), 103-113. https://doi.org/10.1016/S0304-4238(02)00058-4

Paul C, Gomasta J, Hossain MM. 2017. Effects of planting dates and variety on growth and yield of strawberry. International journal of Horticulture, Agriculture and Food Science 1(4), 1-12. https://dx.doi.org/10.22161/ijhaf.1.4.1

Pérez de Camacaro M, Mogollón N, Ojeda M, Giménez A, Colmenares C. 2009. The effect of gibberelic acid on the growth and flowering of strawberry (*Fragaria* × *ananassa* Duch.) ‘Chandler’ vitro plants. Acta Horticulturae 842, 793-796. https://doi.org/10.17660/ActaHortic.2009.842.174

R Core Team. 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/.

Rathod KD, Ahlawat TR, Kumar S, Sarkar M, Chakraborty B. 2021. Effect of plant growth regulators on growth, yield and quality of strawberry (*Fragaria* x *ananassa* Duch.) Cv. Winter Dawn under Open Field Conditions of South Gujarat. Agricultural Science Digest 41(2), 323-333. http://dx.doi.org/10.18805/ag.D-5240

Roopendra K, Sharma A, Chandra A, Saxena S. 2018. Gibberellin-induced perturbation of source–sink communication promotes sucrose accumulation in sugarcane. 3 Biotech, 8, 1-13. https://doi.org/10.1007%2Fs13205-018-1429-2

Sabagh AE, Mbarki S, Hossain A, Iqbal MA, Islam MS, Raza A, Farooq M. 2021. Potential role of plant growth regulators in administering crucial processes against abiotic stresses. Frontiers in Agronomy 3, 648694. https://doi.org/10.3389/fagro.2021.648694

Sage RF, Kubien DS. 2007. The temperature response of C3 and C4 photosynthesis. Plant, Cell & Environment 30(9), 1086-1106. https://doi.org/10.1111/j.1365-3040.2007.01682.x

Sarker BC, Archbold DD, Geneve RL, Kester ST. 2020. Rapid in vitro multiplication of non-runnering *Fragaria vesca* Genotypes from seedling shoot axillary bud explants. Horticulturae 6(3), 51. https://doi.org/10.3390/horticulturae6030051

Sarker BC, Gomasta J. 2024. Technique, Time, and Etiolation Applications Influencing the Grafting Success in Avocado (*Persea americana* Mill.). International Journal of Horticultural Science and Technology 11(2), 147-162. https://doi.org/10.22059/ijhst.2023.360030.645

Shah SH, Islam S, Mohammad F, Siddiqui MH. 2023. Gibberellic acid: A versatile regulator of plant growth, development and stress responses. Journal of Plant Growth Regulation 1-22. https://doi.org/10.1007/s00344-023-11035-7

Sharma RR, Singh R. 2009. GA_3 influences incidence of fruit malformation, berry yield and fruit quality in strawberry (*Fragaria* × *ananassa* Duch.). Acta Horticulturae 842, 737-740. https://doi.org/10.17660/ActaHortic.2009.842.160

Uddin ASMM, Gomasta J, Islam MT, Islam M, Kayesh E, Karim MR. 2024. Gibberellic acid spray modulates fruiting, yield, quality, and shelf life of rambutan (Nephelium lappaceum L.). Journal of Horticultural Research 32(1), 51-66. https://doi.org/10.2478/johr-2024-0004

Wang SY, Camp MJ. 2000. Temperatures after bloom affect plant growth and fruit quality of strawberry. Scientia Horticulturae 85(3), 183-199. https://doi.org/10.1016/S0304-4238(99)00143-0.

Yang J, Song J, Jeong BR. 2024. Flowering and runnering of seasonal strawberry under different photoperiods are affected by intensity of supplemental or night-interrupting blue light. Plants 13(3), 375. https://doi.org/10.3390/plants13030375

Zhang X, Zhao B, Sun Y, Feng Y. 2022. Effects of gibberellins on important agronomic traits of horticultural plants. Frontiers in Plant Science 13, 978223. https://doi.org/10.3389/fpls.2022.978223