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Optimising Okra (*Abelmoschus esculentus* L. Moench.) Fruit Yield and Physiological Responses Through the Integration of Foliar Fertiliser at Different Timings

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ABSTRACT

Okra is an important vegetable crop with high nutritional and economic value. Various approaches have been attempted to increase its production, including foliar fertilisers. This study aims to determine the optimal time to apply foliar fertiliser in a day to improve the final yield in *Abelmoschus esculentus* L. var. Torpedo and evaluate okra's growth and yield responses by integrating foliar fertiliser as supplementary fertiliser with granule fertiliser in a controlled environment. The study was conducted in a rain shelter under a randomised complete block design with 3 blocks comprising 3 replications within each block. The treatments involved a combination of foliar and granule application at different timings: sunrise, midday, and dusk, and solely granule fertiliser at labelled recommended rates. The control group was treated with only granule fertiliser at the same rate as the combined foliar and granule application. The study found that the application of foliar fertiliser during dusk (6–7 p.m.) showed a higher trend of potential yield, which revealed the potential of dusk foliar fertiliser application timing as the optimal

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timing for foliar fertilisation. The study also demonstrated that incorporating liquid foliar fertiliser with granular fertiliser can enhance nutrient uptake and promote plant growth, leading to a more sustainable farming practice by reducing inorganic soil granule fertilisers. The potential yield under the combined fertiliser treatments was 5% to 20% higher when compared to experiment control while comparable to the conventional fertiliser application treatment, despite using 45% less nitrogen. Therefore, the study suggests that farmers integrate foliar and soil fertilisation methods to achieve optimal crop yield production and promote sustainable farming.

Keywords: *Abelmoschus esculentus* L., foliar fertiliser timing, growth, integration fertiliser application, yield responses

INTRODUCTION

Okra (*Albelmoschus esculentus* L. Moench), also known as ladyfinger, is a flowering shrub that belongs to the Malvaceae family. Okra is cultivated globally in tropical and warm temperate regions for the nutritious, fibrous fruit pods (Anwar et al., 2020). Okra pod is one of the most affordable sources of vitamins, minerals, and antioxidants essential for good health (Schreinemachers et al., 2018). According to the United States Department of Agriculture (2019), each 100 g of raw okra pod contains 89.6 g water, 33 kcal energy, 1.93 g protein, 7.45 g carbohydrates, and 0.19 g fat. Also, raw okra is a rich source of dietary fibre, vitamin C, vitamin K, and antioxidants.

Okra is among Malaysia's ten most consumed vegetable crops, with 1.7 kg per capita consumption (Department of Statistic Malaysia [DOSM], 2021). However, Malaysia is still importing okra, and the demand for okra has risen over the past several years. It is reflected in the increment of okra per capita consumption (PCC) (DOSM, 2018, 2020, 2021). Therefore, improving the local production of vegetables is imperative to mitigate this inadequacy. Several factors, such as soil nutrition, seed quality, climate, cultural practices, and the use of plant growth regulators, influence the growth and yield of okra (Shahid et al., 2013), and inadequate soil nitrogen has been identified as a leading cause of low yield, hindering okra production (Ajayi et al., 2017).

Applying foliar fertilisers is one of the many ways to improve crop quality, yield, and metabolism (Fernández & Brown, 2013). Foliar fertiliser or foliar feeding is a technique of feeding plants by applying liquid fertiliser directly to the leaves instead of in the soil. Typically, foliar application has been used to supply major or minor nutrients, plant hormones, and other supplemental matters. Moreover, the integration of foliar fertiliser into a conventional granule fertiliser regimen has been shown to increase the yield of okra crops (Abbasi et al., 2010; Afe & Oluleye, 2017) while simultaneously reducing the need for inorganic soil granule fertilisers and, thus, promotes more sustainable farming practice by minimising soil salinity accumulation (Niu et al., 2020). However, the penetration and absorption of foliar-applied nutrients into the plant surfaces are affected by various environmental factors such as light, temperature, and relative humidity (Fernández et al., 2013), and these environmental factors vary throughout the day.

Current knowledge on the effects of differential foliar timing application in a day on crop yield is limited. Previous studies on the optimum timing of foliar application for enhancing crop yield have focused mainly on certain plant growth stages, such as early tillering for wheat (Peirce et al., 2019) or a certain number of days after planting for okra (Mehraj et al., 2015). This study aims to determine the optimum time to apply foliar fertiliser in a day to improve the final yield in *A. esculentus* L. var. Torpedo (okra) and evaluate okra's growth and yield responses by integrating foliar fertiliser in a controlled environment. It hypothesises that the leaves' uptake and assimilation to nutrients obtained through foliar application would be more responsive at a certain time during the day, and there is a specific time for the foliar application that would improve okra's yield and harvest quality. Also, it is hypothesising that the combined use of foliar and conventional granule fertiliser regimens has been demonstrated to produce a superior crop yield, even when applied at lower rates than the use of granule fertiliser alone. Understanding the contribution of granular and foliar liquid NPK fertilisers to the growth and final yield of okra is essential to recommend it to farmers for improving crop production.

MATERIALS AND METHODS

Experimental Location and Growing Conditions

The experiment was conducted in a rain shelter located at Field 15, Faculty of Agriculture, UPM, with a latitude of 2.99°N and a longitude of 101.74°E. The seeds were sown and grown under rain shelter conditions with an average temperature and relative humidity of 29.2°C and 75.57%, respectively.

Planting Materials and Media

The okra seeds cv. 551 Torpedo (Sin Seng Huat Seeds, Malaysia) were incubated in a plastic container at 100% relative humidity (RH). After 24 hr, the seeds of okra cv. Torpedo was sown in a 12-hole germination box with a box size of 19 cm (L) × 11 cm (W) × 14.5 cm (H), and each planting hole sized 4 cm (L) × 4 cm (W) × 5.5 cm (D). The medium used in the germination tray and polybag was a mixture of silty clay soil (0.80% sand, 54.20% silt, and 45.10% clay, 1.30% organic carbon, pH 4.74) with local commercial soil (Smart Grow Plant Lover 6 in 1 Organic Soil Potting Mix, Baba, Malaysia) at 1:1 volume ratio. Each germination tray was placed in a reservoir dish containing only tap water. After 7 days after sowing (DAS), the okra seedlings were transplanted from the germination tray into a 40.64 cm × 40.64 cm polybag and maintained until 57 DAS.

Agronomic Practices

The agronomic practices were conducted as growth maintenance to maintain the okra plants throughout the experiment. These practices included irrigation, pest control, and weeding. The irrigation method is based on a bottom-up concept by placing the plants in a custom-made reservoir about 1 m in diameter the size of the water reservoir. Water in the reservoir was replenished every 1–3 days, depending on the water level. Pest control was carried out using organic pesticides and installing yellow sticky traps. Wood vinegar was sprayed on the plant foliage as an organic pesticide at a concentration of 5% (v/v) with an application frequency of once a week.

Treatment Applications

The experiment involved five different fertiliser treatments, with the first three involving the combination of foliar and granule fertiliser applied at different times: sunrise, midday, and dusk. The foliar spray (Agroniche, Malaysia) was adjusted to an electrical conductivity (EC) of 1.8–2.2 mS/m (Toh et al., 2022) and applied at a rate of 10 s/plant (approximately 40 ml) with a nitrogen rate of 2.4 kg N/ha. The granular NPK 16-10-10 fertiliser (Sin Seng Huat Seeds, Malaysia) was applied at 28 kg N/ha with 0.86 g per polybag, resulting in a total nitrogen rate of 30.4 kg N/ha. The fourth treatment involved the conventional fertiliser method, using only granular NPK 16-10-10 fertiliser (Sin Seng Huat Seeds, Malaysia) at the product-labelled recommended rate of 350 kg/ha (56 kg N/ha), applied at 1.72 g/polybag. The fifth treatment was the experiment control, which used only granular NPK 16-10-10 (Sin Seng Huat Seeds, Malaysia) at 30.4 kg N/ha, applied at 0.93 g/polybag. The fertilisers were applied to okra plants beginning 14 days after sowing and repeated weekly until the plants reached the reproductive stage 35 days after sowing. A 1% (v/v) concentration of dimethyl sulfoxide (DMSO) (Ninelife, Malaysia) was added to the solution as an adjuvant to enhance the effectiveness of the foliar spray. The summary of the different fertiliser treatments used in the experiment is presented in Table 1.

Data Collection

Light Spectrum Profile. The rain shelter's light spectrum readings were recorded using a spectrometer (LI-180; LI-COR Inc., USA) according to the treatment time (sunrise, midday, and dusk). The spectrometer was placed 110 cm above the ground, and three measurements were taken each time at three sections of the rain shelter, namely the top,

Table 1
Summary of treatment application

No.	Treatment	Fertiliser type/combination	Time of application	Rate
1	F:GSun	Combined fertiliser application (foliar + granule)	Sunrise (7–8 a.m.)	30.4 kg N/ha
2	F:GMid		Midday (1–2 p.m.)	
3	F:GDusk		Dusk (6–7 p.m.)	
4	G:Rec	Granules (labelled recommended rate)	-	56 kg N/ha
5	G:Con	Granule (experiment control)	-	30.4 kg N/ha

middle, and bottom sections of the shelter, to obtain average values of the light spectrum

Vegetative Growth Properties. Plant height (cm) was measured from the ground level until the tip of the apical bud using a measuring tape, and the leaf number of a fully expanded leaf was manually counted (Khor, 2022).

Leaf Physiology. The chlorophyll content was measured using the Soil Plant Analysis Development (SPAD) chlorophyll meter (Chlorophyll meter SPAD-502Plus, Konica Minolta Inc., Japan) on the fully expanded leaf of the sample. Readings were taken three times around the midpoints of the leaf, and the average SPAD index was recorded (Khor, 2022; Toh et al., 2022; Yaapar, 2017). Measurements were taken every week from 13 DAS onwards until the eighth week of the experiment. Leaf gas exchange, including assimilation (A_{400}) and stomatal conductance to water vapour (gs_w), were measured using the LI-6800 photosynthesis system (LI-COR Inc., USA) during the vegetative stage (35-38 DAS). The leaf chamber was selected, and one of the top three to five fully expanded leaves were clipped to measure the leaf physiology parameters (Jusoh et al., 2023; Toh et al., 2022). The light intensity was set at 1,500 µmol/m^2/s, composed of 10% blue and 90% red light, temperature at 27–30°C, and humidity at 60%. The flow setpoint was set at 500 µmol/s, valve 0.1 kPa with a fan speed setting of 10,000 rpm, and the CO_2 was injected into the leaf chamber at 400 ppm (Khor, 2022). Intrinsic water use efficiency (iWUE) was calculated as a ratio of assimilation rate over stomatal conductance (Jusoh et al., 2023; Yaapar, 2017).

Fruit Parameters. The okra pods were harvested 45 days after sowing with a standard pod length of more than 10 cm over 2 weeks. Fruit parameters included fruit number, length, circumference, and weight (on a fresh and dry basis). The fresh and dry fruit weight (g) was measured using an electronic weighing balance (FX-1200i, A&D, CO. Ltd., Japan). The fruits were dried at 60°C in an oven (UM 400, MEMMERT GmbH + Co. KG., Germany) for 48 hours to obtain the dry weight (g). The potential yield was calculated from the total fresh fruit weight divided by the harvested area and is expressed in the unit of MT/ha.

Fruit Firmness. The fruit firmness was measured using the Instron texture analyser (Model 5543 load frame, Instron Corp., USA) with a p/5 (5 mm diameter) needle probe at a test speed of 20 mm/s. The okra pod was punched three times at equidistance, and the firmness reading was recorded in Newton (N) using the Instron Merlin Software version M12-13664-EN (Khor, 2022).

Fresh and Dry Weight of Shoot and Root. The fresh and dry matter of the shoot and root were determined by using a destructive method. The plant was cleaned and separated into shoot and root parts. The fresh and dry shoot and root weights were measured separately using an electronic weighing balance (FX-1200i, A&D, CO. Ltd., Japan). The shoots were then cut into small pieces, and roots were placed in paper bags and dried for 48 hr at 60°C in an oven (UM 400, MEMMERT GmbH + Co. KG., Germany). The shoot-to-root ratio (S:R) was calculated as a ratio of shoot-dry weight over root-dry weight (Reynolds & Thornley, 1982).

Number and Dry Weight of Seeds. The number of seeds was calculated using CountThings version G 3.69.1 software (CountThings, USA). The dried seeds were weighed using the electronic balance (Original Equipment Manufacturer, China).

Experimental Design and Statistical Analysis. Randomised complete block design (RCBD) was conducted with 3 blocks comprising 3 replications within each block. All data were subjected to the normality test of Anderson-Darling and analysis of variance (ANOVA) at $p = 0.05$ using GraphPad Prism version 9 software (GraphPad Software, USA). The data were also subjected to normality and homogeneity of variance testing to ensure that the data followed the assumption for ANOVA. Whenever significant, means were compared using Tukey's honestly significant difference (HSD) test at $p = 0.05$. Pearson's analysis of the correlation between parameters was also performed in Origin(Pro) 2022 software (OriginLab Corporation, USA) at $p = 0.05$ to determine the strength and direction of correlation between the parameters measured.

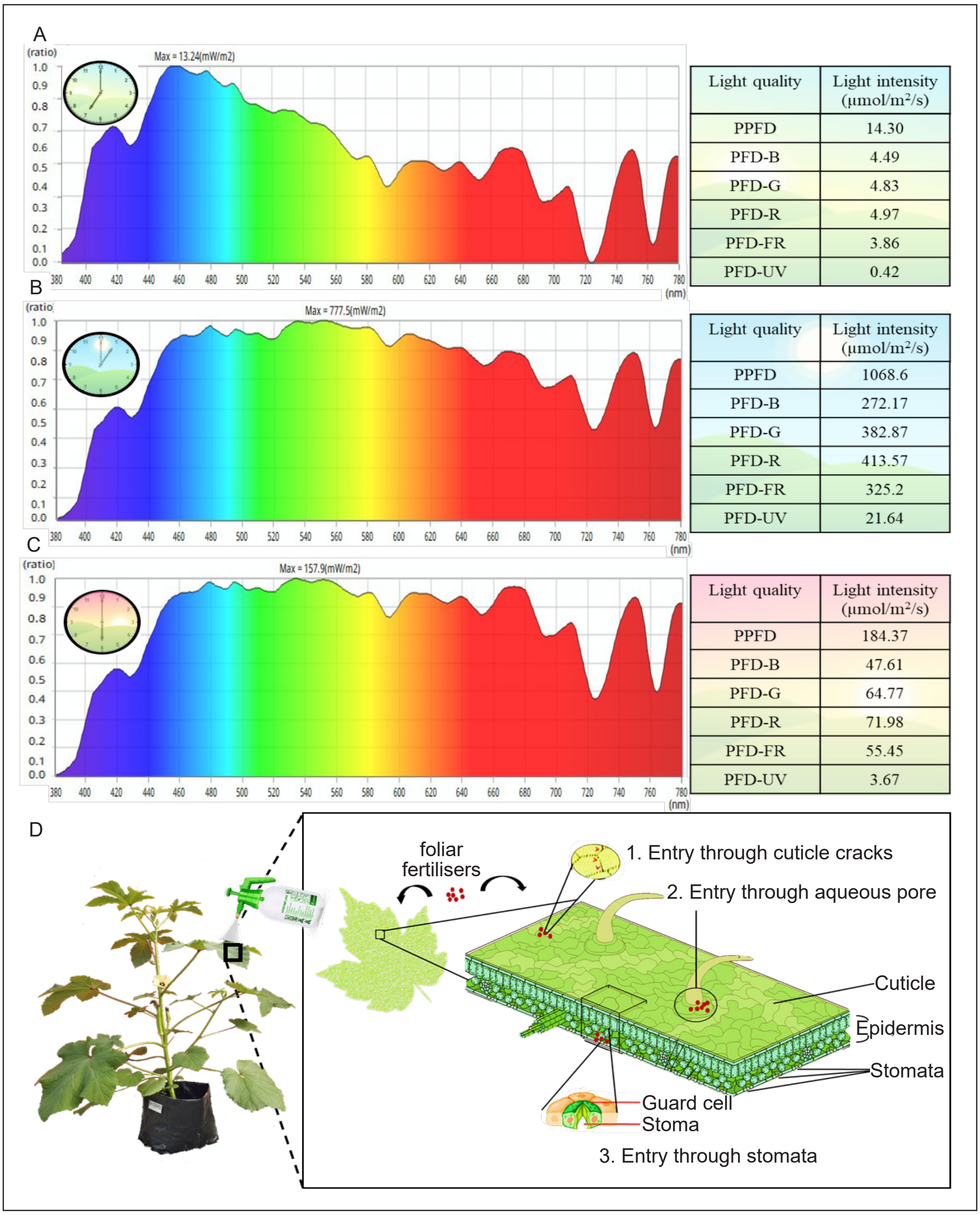
RESULTS

Effects of Periodic Changes of Daytime on Light Spectrum Profile, Temperature, Relative Humidity, and Foliar Nutrient Uptake Pathways

The study recorded light intensity and spectrum at three different times of the day, namely sunrise (7 a.m.), midday (1 p.m.), and dusk (6 p.m.). The highest photosynthetic photon flux density (PPFD) was observed during midday (1,068.6 μmol/m^2/s), followed by dusk (184.37 μmol/m^2/s) and sunrise (14.30 μmol/m^2/s). A similar trend was observed in far-red photon flux density (PFD-FR) and ultra-violet photon flux density (PFD-UV). Temperature and relative humidity were also recorded using CO_2 meters (HT-2000, Hti, Dongguan Xintai Instrument CO. Ltd., China) and tabulated in Table 2. The highest temperature was observed at midday (38.5°C), followed by dusk (27.7°C) and sunrise (25.1°C). Relative humidity was highest at sunrise (88.03%), followed by dusk (75.9%) and midday (52.54%). The foliar nutrients can penetrate the leaf surface through various means, including the cuticle per se, cuticle cracks, or specialised epidermal structures like stomata and aqueous pores at the trichomes' base (Figure 1D).

Table 2
Average temperature and relative humidity corresponding to the foliar application time

Time	Temperature (°C)	Relative humidity (%)
Sunrise (7–8 a.m.)	25.1 ± 2.5	88.03 ± 6.51
Midday (1–2 p.m.)	38.5 ± 3	52.45 ± 7.04
Dusk (6–7 p.m.)	27.7 ± 1.7	75.99 ± 9.81



Light quality	Light intensity (µmol/m²/s)
PPFD	14.30
PFD-B	4.49
PFD-G	4.83
PFD-R	4.97
PFD-FR	3.86
PFD-UV	0.42

Light quality	Light intensity (µmol/m²/s)
PPFD	1068.6
PFD-B	272.17
PFD-G	382.87
PFD-R	413.57
PFD-FR	325.2
PFD-UV	21.64

Light quality	Light intensity (µmol/m²/s)
PPFD	184.37
PFD-B	47.61
PFD-G	64.77
PFD-R	71.98
PFD-FR	55.45
PFD-UV	3.67

Figure 1. (A) The average light spectrum reading of the rain shelter at sunrise. (B) The average light spectrum reading of the rain shelter at midday. (C) The average light spectrum reading of the rain shelter at dusk. The light source value: PFD-R (600–700 nm wavelength range), PFD-G (500–600 nm), PFD-B (400–500 nm), PFD-UV (80–400 nm), and PFD-FR (700–780 nm). (D) The general pathways of foliar nutrient uptake across the leaf surface

Note. PPFD = Photosynthetic Photon Flux Density; PFD-B = Photon Flux Density-Blue; PFD-G = Photon Flux Density-Green; PFD-R = Photon Flux Density-Red; PFD-FR = Photon Flux Density-Far Red; PFD-UV = Photon Flux Density-Ultraviolet

Effects of Differential Foliar Application Timing and Methods on Agronomy Traits

The mean values of agronomy parameters, including plant height, leaf number, total biomass, and shoot-to-root ratio, were presented as a bar graph in Figure 2. The growth appearance corresponding to each treatment is shown in Figure 2A. The highest and lowest plant heights observed in treatment F:GSun (117.42 cm) and REC (105.43 cm), respectively, in Figure 2B. Despite the non-significant difference between treatments, there is a trend of increased plant height under F:GSun treatment by about 6% compared to the regular granule fertiliser method (G:Con). Despite the non-significant difference between treatments, the highest leaf count was observed in treatment G:Con (Figure 2C). It indicated that granule application resulted in higher leaf counts, while the combined application method at midday (F:GMid) tended to lower okra leaf counts.

Regarding biomass accumulation, the G:Rec treatment showed a higher trend of total dry weight, whereas treatment F:GMid resulted in a lower trend of total dry weight (Figure 2D). Among the three application timings, okra plants subjected to dusk application timing (F:GDusk) tended to accumulate more biomass. The shoot-to-root ratio represents the relative biomass allocation between the shoot and the root of a plant. Treatment G:Con has a great tendency to produce a higher shoot biomass partitioning in the okra plant (Figure 2E). Intriguingly, similar agronomic outcomes were observed among the treatments, even though the conventional granule fertilisation treatments (G:Rec) received a higher N rate. Although the differences were not statistically significant, the interpretations of the results were still useful in identifying general tendencies and inclinations in the variables under investigation.

Effects of Differential Foliar Application Timing and Methods on Leaf Physiology

The mean values for leaf physiology parameters, namely total chlorophyll content, assimilation rate (A_{400}), stomata conductance to water vapour (GSW), and iWUE, were presented as bar graphs in Figure 3. There was a significantly highest value of total chlorophyll content observed in treatment G:Rec (Figure 3A). Among the three application timings, the total chlorophyll content was significantly higher in okra plants subjected to dusk application timing (F:GDusk).

Moreover, treatments G:Con and F:GDusk showed a great tendency to result in a higher assimilation rate (Figure 3B). Similarly, treatments G:Con and F:GDusk have the greatest tendency to result in a higher value of gs_w (Figure 3C). Stomatal conductance measures the rate at which water vapour diffuses through the stomatal pores in the leaves of a plant. It reflects the degree of stomatal opening, which is largely controlled by the plant's physiological responses to environmental factors such as light intensity, temperature, humidity, and water availability.

When both A_{400} and gs_w were combined as a ratio to assess iWUE, the okra plants

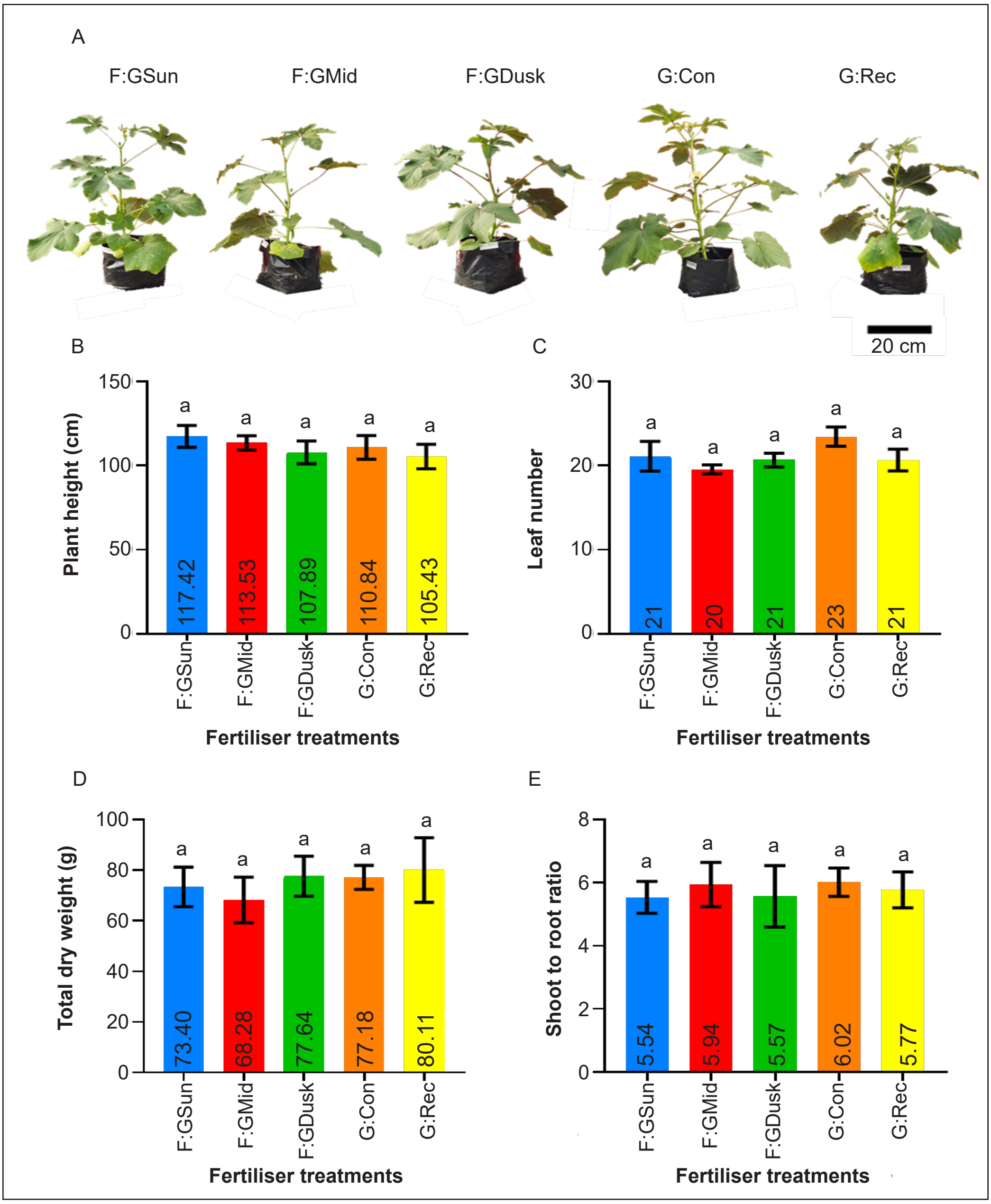


Figure 2. (A) General growth appearance of the okra plant at 42 days after sowing (DAS). (B) Mean comparison of plant height at 57 DAS. (C) Mean comparison of leaf number at 48 DAS. (D) Mean comparison of total dry weight at 57 DAS. (E) Mean comparison of shoot-to-root ratio at 57 DAS. Means with the different alphabets are significantly different using Tukey's honestly significant difference test at $p = 0.05$ (n = 9). Error bars indicate the standard error of means, while the value in the bar indicates the mean value for the respective treatments

Note. F:GSun = Foliar and granule fertiliser at sunrise; F:GMid = Foliar and granule fertiliser at midday; F:GDusk = Foliar and granule fertiliser at dusk; G:Rec = Granule fertiliser at recommendation rate; G:Con = Granule fertiliser at normalise rate as control

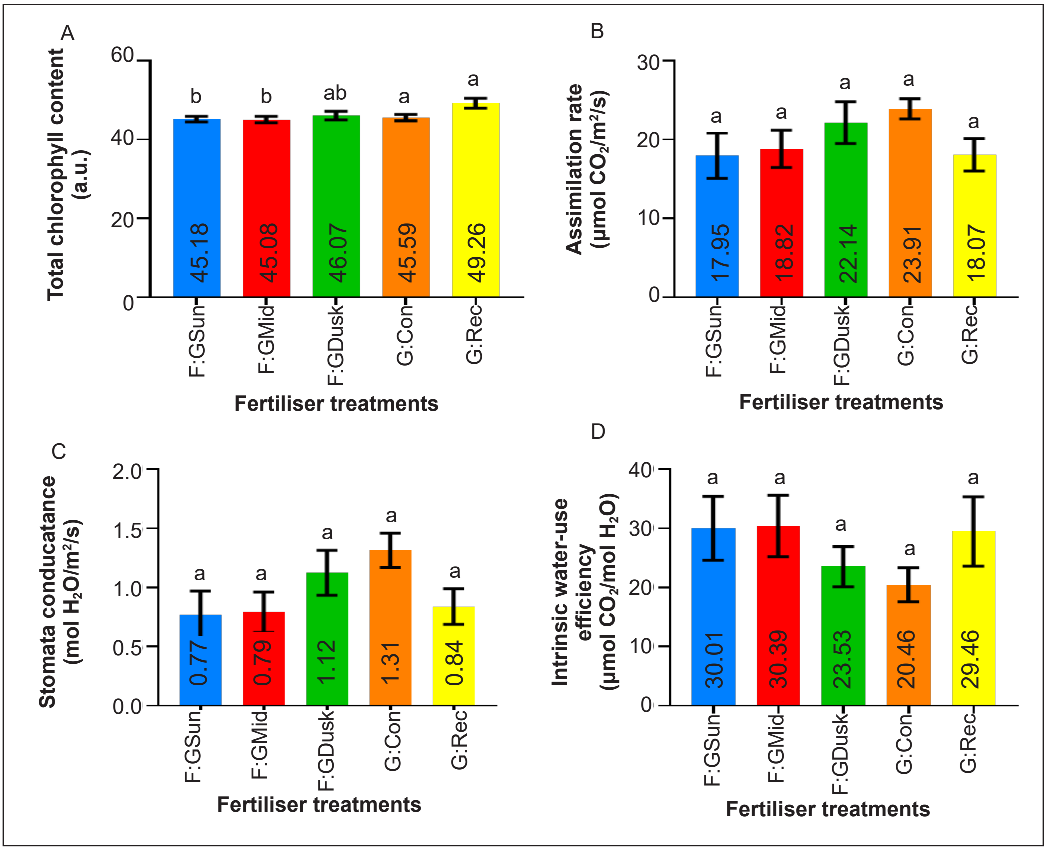


Figure 3. (A) Mean comparison of total chlorophyll at 41 days after sowing (DAS). (B) Mean comparison of assimilation rate. (C) Mean comparison of stomata conductance. (D) The mean comparison of intrinsic water-use efficiency. Means with the different alphabets are significantly different using Tukey's honestly significant difference test at $p = 0.05$ (n = 9). Error bars indicate the standard error of means, while the value in the bar indicates the mean value for the respective treatments

Note. F:GSun = Foliar and granule fertiliser at sunrise; F:GMid = Foliar and granule fertiliser at midday; F:GDusk = Foliar and granule fertiliser at dusk; G:Rec = Granule fertiliser at recommendation rate; G:Con = Granule fertiliser at normalise rate as control

treated with treatments F:GSun, F:GMid, and G:Rec exhibit a relatively high value of iWUE (Figure 3D), and these plants are expected to tolerate drought condition well.

Effects of Differential Foliar Application Timing and Methods on Okra Fruit Parameters

The mean values of okra fruit parameters such as fruit length, fruit middle section circumference, fruit firmness, fruit fresh weight, fruit dry weight, total fruit number, and potential yield were presented as bar graphs in Figure 4. The general morphological characteristics of "Torpedo" okra fruits corresponding to each treatment are shown in Figure 4A.

In terms of fruit length, middle section circumference, and firmness, the treatment G:Con showed significantly lower values

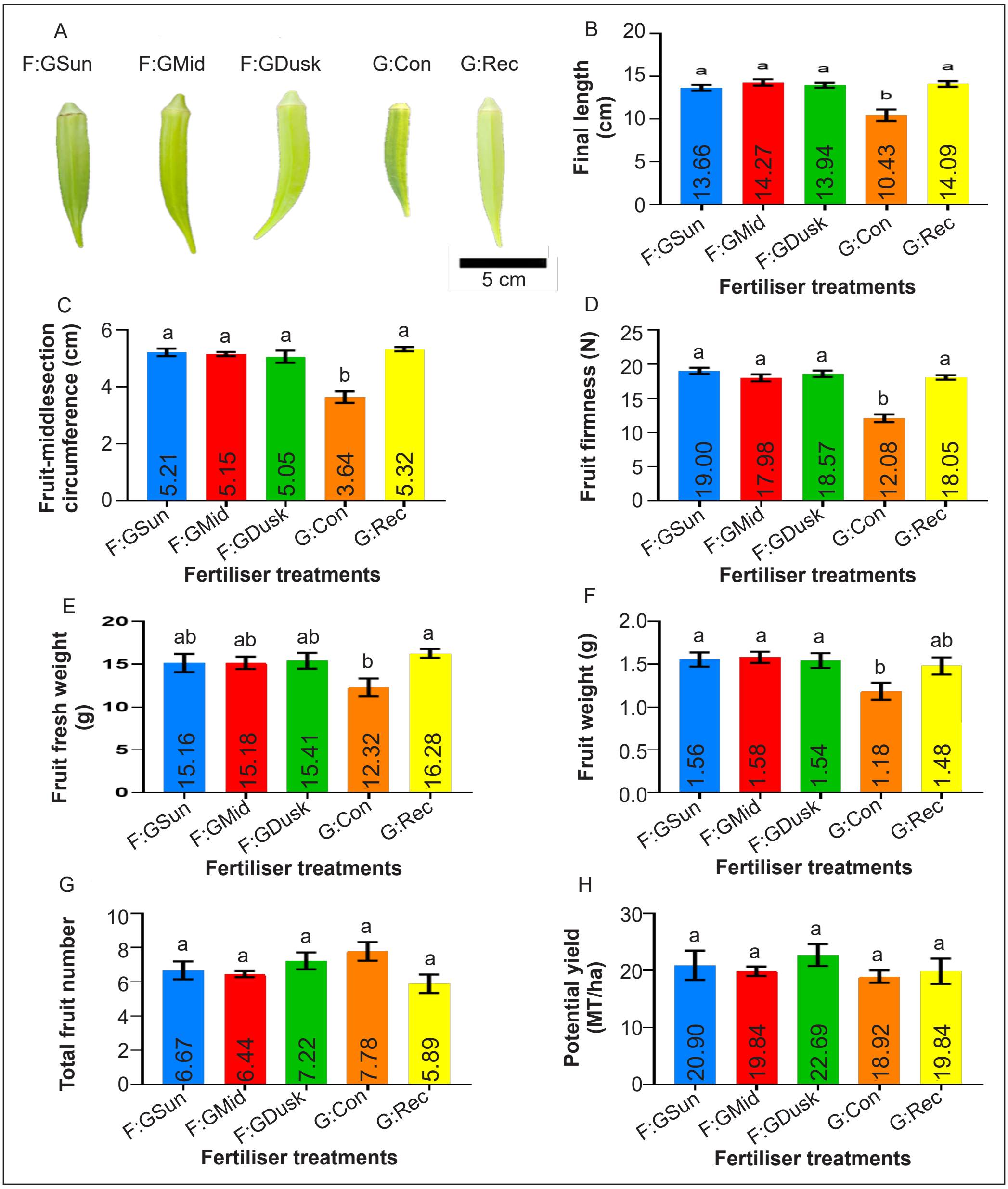


Figure 4. (A) The morphological characteristic of "Torpedo" okra fruits corresponding to each treatment. (B) Mean comparison of average fruit length. (C) Mean comparison of average fruit perimeter. (D) Mean comparison of the average fruit firmness. (E) Mean comparison of average fruit fresh weight. (F) Mean comparison of average fruit dry weight. (G) Mean comparison of total fruit number harvested over 2 weeks of the period. (H) Mean comparison of potential yield calculated. Means with the different alphabets are significantly different using Tukey's honestly significant difference test at $p = 0.05$ (n = 9). Error bars indicate the standard error of means, while the value in the bar shows the mean value for the respective treatments

Note. F:GSun = Foliar and granule fertiliser at sunrise; F:GMid = Foliar and granule fertiliser at midday; F:GDusk = Foliar and granule fertiliser at dusk; G:Rec = Granule fertiliser at recommendation rate; G:Con = Granule fertiliser at normalise rate as control

compared to the other treatments that were tested. In addition, there was a slightly higher tendency for the F:GMid treatment to result in longer fruit length (Figure 4B), while the G:Rec treatment showed a slightly higher tendency to result in larger fruit circumference (Figure 4C). These results suggest that the timing and incorporation of foliar fertiliser applications may affect fruit size, although the effect may be relatively small. Similarly, the fruit firmness was quantified by the force (N) needed to penetrate the fruit surface tissue, and the maximum resistance force (N) was recorded. The higher the value indicates, the harder the fruit pods. F:GSun treatment has a greater tendency to result in harder fruit pods, while treatment G:Con resulted in significantly softer fruit pods (Figure 4D).

Moreover, findings depicted in Figure 4E indicate that treatment G:Rec exhibited a higher propensity to yield greater fresh fruit weight, while the lowest fresh fruit weight was observed in G:Con. Moreover, a higher trend of dry fruit weight was observed in treatment F:GMid, while the lowest dry fruit weight was observed in G:Con (Figure 4F).

Furthermore, more fruits were harvested in the treatments G:Con and F:GDusk (Figure 4G). As a result, treatment F:GDusk showed a greater tendency to higher potential yield by about 20% compared to G:Con.

Effects of Differential Foliar Application Timing and Methods on Okra Seed Parameters

Seed parameters are essential to the seed industry to produce high-quality and consistent seeds as planting material. Seed number (SN) is among the important parameters to indicate the seed yield, while the seedling vigour is significantly

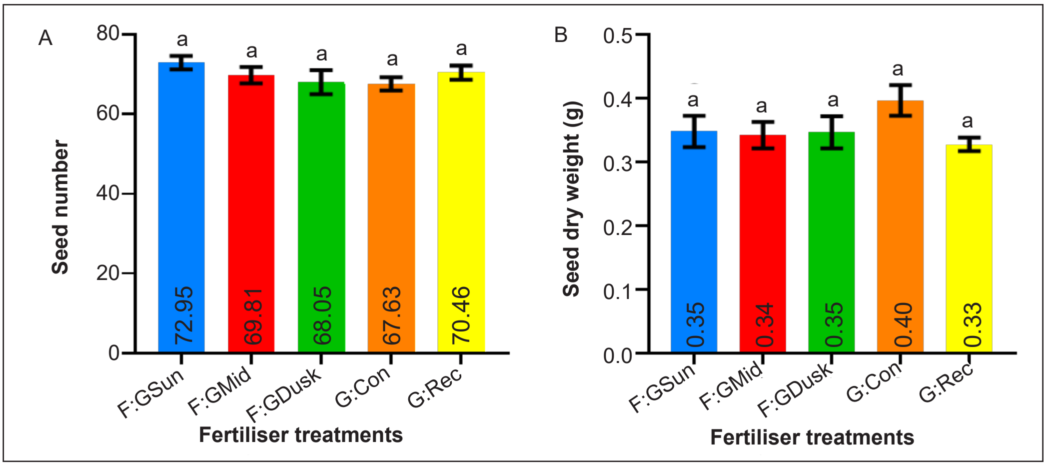


Figure 5. (A) Mean comparison of seed number. (B) Mean comparison of seed dry weight. Means with the different alphabets are significantly different using Tukey's honestly significant difference test at $p = 0.05$ (n = 9). Error bars indicate the standard error of means, while the value in the bar indicates the mean value for the respective treatments

Note. F:GSun = Foliar and granule fertiliser at sunrise; F:GMid = Foliar and granule fertiliser at midday; F:GDusk = Foliar and granule fertiliser at dusk; G:Rec = Granule fertiliser at recommendation rate; G:Con = Granule fertiliser at normalise rate as control

influenced by the seed weight (Kandasamy et al., 2020; Zhang et al., 2017).

Non-significant differences in the SN parameter were observed between treatments; however, combined foliar fertiliser application at sunrise (F:GSun) has a greater tendency to result in higher SN (Figure 5A). The SN was about 7.8% higher when compared to treatment G:Con. On the other hand, treatment G:Con tended to produce a higher dry weight for the seed (Figure 5B).

Heatmap Plot Representing the Correlation Matrix Between the Growth, Physiology, Fruit, and Seed Parameters

Pearson's correlation analysis was carried out to comprehend the strength of the relationship between the growth, physiology, fruit, and seed parameters (Figure 6). The results of the study showed strong to moderate positive correlations between various fruit parameters, including fruit length (FL), fruit circumference (FC), fruit

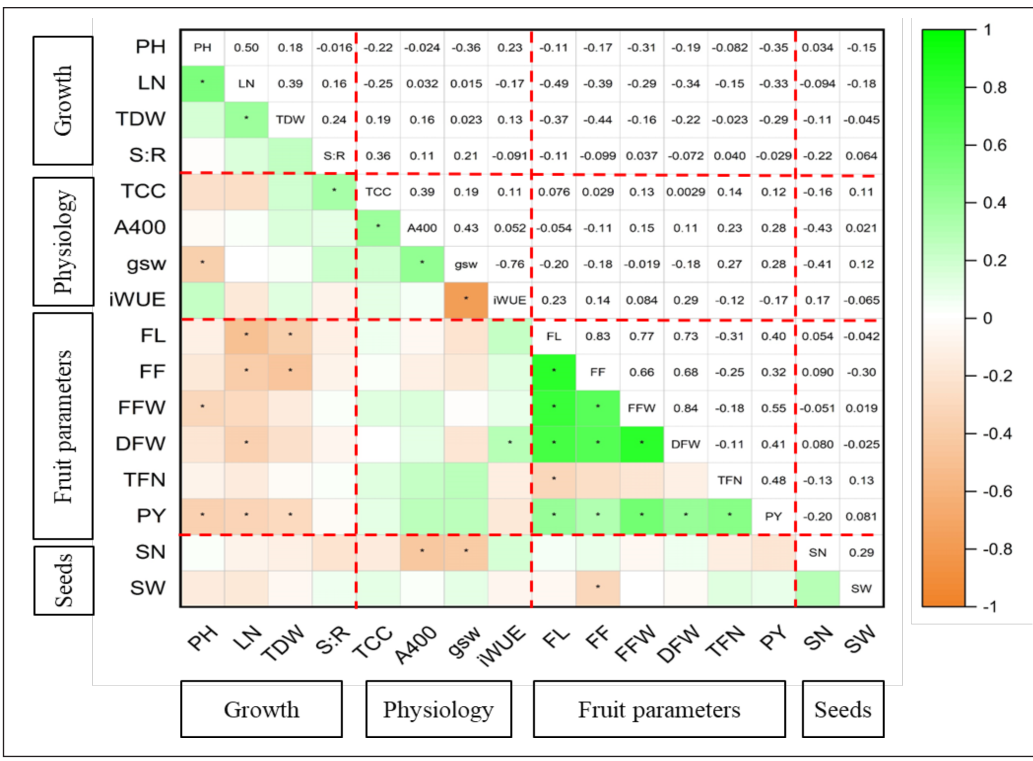


Figure 6. The correlation heatmap analysis represents the strength of correlations between the growth, physiology, fruit, and seed parameters. Pearson's correlation coefficient is used as the correlation descriptor (green and orange for positive and negative correlations, respectively). Symbol * represents a significant difference at $p < 0.05$. Correlation coefficients have a value of between -1 and 1. A "0" means no relationship between the variables, while -1 or 1 means a perfect negative or positive correlation.

Note. PH = Plant height; LN = Leaf number; TDW = Total dry weight; S:R = Shoot to root ratio; TCC = Total chlorophyll content; A_{400} = Assimilation rate; gs_w = Stomata conductance to water vapor; iWUE = Intrinsic water use efficiency; FL = Fruit length; FC = Fruit circumference; FF = Fruit firmness; FFW = Fresh fruit weight; DFW = Dry fruit weight; TFN = Total fruit number; PY = Potential yield; SN = Seed number; SW = Seed dry weight firmness (FF), fresh fruit weight (FFW), dry fruit weight (DFW), and potential yield (PY). Moreover, high to moderate positive correlations were found between PY and other fruit parameters, such as FL, FC, FF, FFW, DFW, and total fruit number (TFN). Similarly, moderate positive correlations were observed between leaf physiology parameters, such as assimilation rate (A_{400}), total chlorophyll content (TCC), and stomata conductance to water vapour (gs_w), as well as between growth parameters, such as leaf number (LN), plant height (PH), and total dry weight (TDW).

In contrast, moderate negative correlations were observed between certain growth and physiology parameters. LN had moderate to low negative correlations with FL, FC, FF, DFW, and PY, while TDW was negatively correlated with FL, FC, FF, and PY. Additionally, PH was negatively correlated with FFW and PY. Furthermore, the study showed a strong negative correlation between the physiology parameters, namely gs_w and iWUE, while a moderate negative correlation between SN, A_{400}, and gs_w.

DISCUSSION

This experiment studied the effect of foliar application timing and mode on four components of crop performance in okra: plant growth, leaf physiology, fruit, and seed yield. In search of the optimum daytime for the NPK foliar fertiliser application, this study identified the potential of dusk application timing (6–7 p.m.) that tends to result in a better efficiency of nutrient uptake and assimilation, which was reflected in the assimilation rate, total fruit number and potential yield parameters (Figures 3B, 4G, and 4H). This finding is consistent with a previous study on the optimal timing of foliar fertilisation, which reported that the late afternoon period was the most suitable time for foliar fertiliser application (Fageria et al., 2009).

Foliar penetration and assimilation are processes that are influenced by the metabolic status of plants, which, in turn, are regulated by environmental factors such as light, temperature, and humidity (Fernández et al., 2013; Niu et al., 2020). Light signals are particularly dynamic, varying with time, seasons, and the circadian clock (Xu et al., 2021), and have been shown to play a critical role in nutrient uptake and utilisation by plants (Chen et al., 2016; Cui et al., 2019; Lin et al., 2020; Sakuraba & Yanagisawa, 2018). Evidence suggests that light intensity profoundly affects plant ion uptake (Xu et al., 2021), as exemplified in *Brassica campestris*, where the nitrate content decreased significantly under low light intensity (Xin et al., 2009).

Furthermore, light intensity significantly alters the photosynthetic efficiency of plants, resulting in dynamic changes in sugar accumulation in plants (Xu et al., 2021). An earlier study implicated that light increased plant N uptake by enhancing plant photosynthesis and affecting sugar accumulation (Delhon et al., 1996; Xu et al., 2021). Light intensities between 100-800 μmol/m^2/s are typically sufficient to drive photosynthesis in most plants (Hofmann et al., 2016). The light spectrum result (Figure 1C) of this experiment suggests that the optimal time for foliar fertiliser application is during dusk (6–7 p.m.), as this period achieves the necessary light conditions to drive photosynthesis, with an average light intensity of 184.37 μmol/m^2/s.

In addition, the ideal temperature for foliar application in tropical regions varies depending on the specific crop but typically ranges from 18 to 29°C while the optimum relative humidity is above 70% (Alshaal & El-Ramady, 2017). Temperature and relative humidity primarily play an essential role in the drying rate of the sprayed nutrient droplets (Fernández et al., 2013). High relative humidity delays rapid nutrient solution drying (Fernández et al., 2013; Gooding & Davies, 1992) and causes the swelling of the cuticular membrane, which favours the absorption of foliar fertiliser (Fernández et al., 2021; Schönherr & Schreiber, 2004). In combination with the optimal light intensity, temperature (27.7°C), and relative humidity (75.9%) for dusk application (Figure 1C, Table 2), the effectiveness of the foliar fertiliser was further improved, ultimately resulting in a promising yield and plant growth.

Moreover, light intensity was highest at midday, leading to increased photosynthesis and plant sugar accumulation. However, when the light energy absorbed by the photosynthetic apparatus exceeds the utilisation demand, excess light energy causes a decrease in the conversion efficiency of light energy (Bassi & Dall'Osto, 2021). Therefore, excessive light intensity can lead to the generation of destructive singlet oxygen and other active substances in the photosynthetic organs (Patelou et al., 2020), causing oxidative damage to thylakoid membranes and impairing photosynthetic processes (Yin et al., 2010), ultimately attenuating the positive effect on nutrient absorption (Xu et al., 2021). In addition, high light intensity during midday is usually associated with high temperatures and low relative humidity, directly and indirectly reducing foliar uptake and assimilation by plants. High temperature speeds up the drying rate of the foliar nutrients by increasing the rate of evaporation from the spray solutions deposited onto the foliage (Fernández et al., 2013; Niu et al., 2020).

Despite the application time, it is worth mentioning that integrating foliar fertiliser into conventional granule fertiliser application is a promising approach to improving nutrient uptake and utilisation while reducing the usage of inorganic soil granule fertilisers. It promotes more sustainable farming practices by minimising soil salinity accumulation. The potential yield under the combined fertiliser treatments was 5 to 20% higher when compared to the experiment control. Moreover, the overall results presented in Figures 2, 3, 4, and 5 showed that crop performance under combined fertiliser treatments (F:GSun, F:GMid, and F:GDsuk) was statistically similar, with no significant differences, to the conventional fertiliser application treatment (REC), despite the N rate being about 45% lower than that of the G:Rec treatment. Similar results were reported by Abbasi et al. (2010) as well as Afe and Oluleye (2017), who found that the combination of soil application and foliar fertilisation was promising in enhancing okra's growth and yield traits.

The foliar application of nutrients provides plants with readily available nutrients, promoting faster growth and increased productivity by reducing the distance the nutrients travel within the plant (Simarmata et al., 2021). In addition, the combined fertilisation methods further improve plant growth by providing essential micronutrients that may be lacking in granule fertilisers. Also, micronutrients applied through soil application may be lost to the environment or temporarily accumulate in the soil due to complex soil chemistries, hindering their immediate availability for plant uptake (Bindraban et al., 2015; Sebilo et al., 2013; Thakur & Kumar, 2020). Plant nutrient uptake is a complex process involving multiple transporters, often transporting more than one nutrient type. For instance, the iron-regulated transporter (Irt), which is stimulated by Fe deficiency, facilitates the transportation of Fe, Mn, Cu, Zn, and possibly other divalent cations into the plant (Quintana et al., 2022; Rai et al., 2021; Sinclair & Krämer, 2012), leading to competition and antagonism due to the shared uptake and transport systems of these ions (Bindraban et al., 2015). Thus, applying the combined fertilisation method allowed the plant to absorb nutrients through various pathways, including the root and shoot, while reducing the likelihood of antagonism.

An additional advantage of combining foliar and granule application can be achieved by exploiting synergistic effects (Bindraban et al., 2015; Niu et al., 2020). Many studies have suggested that the nutrient elements and other constituents of foliar fertiliser formulations may stimulate the uptake of soil-applied fertilisers (Niu et al., 2020). Oprica et al. (2014) demonstrated that supplementing a combination of nitrogen, phosphorus, potassium, iron, copper, and manganese via foliar application resulted in improved nutrient levels in the leaves and seeds of maise and sunflower, along with a 50% increase in yield compared to using only NPK as the basal application. The N isotopic tracer technique demonstrated that cotton plants had a higher nitrogen uptake efficiency of 28% and accumulated 11.35 mg of nitrogen via root uptake with ammonium N treatment after foliar application compared to the water control treatment (Cangsong et al., 2018). The increased uptake of nitrogen was a result of the positive impact of foliar nutrients on root proliferation, growth, and development, resulting in better anchorage and deep penetration of root into the soil, which led to a greater amount of nutrient uptake from the rhizosphere (Prajwal Kumar et al., 2018). Foliar nutrients can be absorbed and transported through the stem to the roots, thus enhancing root activity and preventing premature senescence of the roots, thereby enhancing the absorptive capacity of the roots; this interaction makes the combination of soil and foliar fertilisation a relevant practice (Niu et al., 2020).

CONCLUSION

It is ascertained that integrating liquid foliar fertiliser with the basal applied granular fertiliser could be a promising approach for enhancing nutrient uptake and promoting plant growth. Hence, it is recommended that farmers integrate foliar and soil fertilisation practices for optimal okra yield production. Furthermore, it is plausible to infer that the optimal timing for foliar fertilisation is during dusk (6–7 p.m.) when environmental factors such as ideal levels of light, temperature, and relative humidity converge to create favourable conditions for efficient absorption of nutrients applied through the foliage. This observation holds significant scientific significance as it underscores the importance of timing in achieving optimal foliar fertilisation efficacy, which can be instrumental in promoting healthy plant growth and enhancing okra yields. However, it is worth noting that the study results only account for the optimal timing of foliar fertilisation during dusk, and further research is required to evaluate the efficacy of other application timings. Notwithstanding, it is hypothesised that morning application between 8 and 9 a.m. could potentially result in superior outcomes compared to an earlier application window of 7 to 8 a.m., although additional research would be necessary to confirm this hypothesis. Therefore, by carefully timing foliar fertilisation and combining it with appropriate soil fertilisation techniques, farmers can enhance the nutrient uptake of their crops, promote healthy plant growth, and ultimately increase their yields.

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