Original Research Article

**Chlorophyll Fluorescence as an Indicator for The Performance of Tomato Seedlings under The Illumination of LEDs**

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**Highlights**

* The chlorophyll fluorescence model is a fast and simple method and non-invasive means of estimating light employment in Photosystem II (PS II).
* There are many devices developed for chlorophyll fluorescence determination that exist and used.
* The puddle model is the older model for quenching protocol, which uses qP for estimation of photochemical quenching and NPQ for non-photochemical quenching.
* chlorophyll fluorescence measurements approaches were used to evaluate the best-LED light quality that produce strong seedlings of tomato cultivars based on its physiological performance.

**Abstract**

The chlorophyll fluorescence model is a fast and simple method and non-invasive means of estimating light employment in Photosystem II (PS II). This study assesses the aspect related to the thoroughness and applicability of chlorophyll fluorescence for the measurement of PS II photochemical quantum yield in intact leaves of tomato seedlings. In this research, we provided advice and protocols for fast timescale chlorophyll fluorescence measurements using a handheld apparatus in the laboratory or in the field. The parameters of chlorophyll fluorescence under different qualities of LED light were estimated. It was found that, the best treatments for physiological performance were a mixture of red and blue light with high ratio of red light, it leded to increase in both of Effective quantum yield of PSII photochemistry Y(II), Photochemical quenching (qP) and Electron transpolrt ratio (ETR), while the mixture of red and blue light with high ratio of blue light, it leded to increase in Non-photochemical quenching (NPQ). Based on this study, we found that the technique is suitable for applications in circumstances where rapidity, convenience, and sensitivity are required for evaluating the quality of tomato seedlings, while the interpretation of some measured parameters demands wariness.

**Keywords*:***

*LED light, Effective quantum yield of PSII photochemistry (Y(II)), Non-Photochemical Quenching (NPQ) , Photochemical Quenching (qP), Electron Transport Rate (ETR).*

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| **Abbreviations:** | | | |
| **R** | Red light 100% | **Y(NO)** | The quantum yield of non-regulated energy dissipation in PSII |
| **R7:B3** | Red and Blue lights with a ratio of 70:30% | **(Fv/Fm)** | Maximum photochemical efficiency of PSII |
| **R5:G2:B3** | Red, Green and Blue lights with a ratio of 50:20:30% | **(ΦPSII)** | Quantum efficiency of PSII |
| **R3:G2:B5** | Red, Green and Blue lights with a ratio of 30:20:50% | **(NPQ)** | Non-Photochemical Quenching |
| **R3:B7** | Red and Blue lights with a ratio of 30:70% | **(qP)** | Photochemical Quenching |
| **B** | Blue light 100% | **(ETR)** | Electron Transport rate |
| **WFL** | White Fluorescent Lamps | **PAR** | Photosynthetic active radiatio |
| **Y(II)** | Effective quantum yield of PSII photochemistry | **J** | *(Solanum lycopersicum var. Gangmu No.1(钢木1号))* |
| **Y(NPQ)** | The quantum yield of regulatory energy dissipation in PSII | **M** | *(Solanum lycopersicum var. Millennium (千禧))* |

# Introduction

Chlorophyll fluorescence is the term refers to the light re-radiated by chlorophyll atoms during the process from energized to non-energized states. It is utilized as a pointer of photosynthetic energy transformation in higher plants, algae, and bacteria. Energized chlorophyll disperses the consumed light energy by driving photosynthesis (photochemical energy conversion), as the heat in non-photochemical quenching or as a fluorescence radiation. As these processes are correlative, the examination of chlorophyll fluorescence is a significant instrument in plant’s light metabolism due to its wide spectrum of applications ([Lu et al., 1999](#_ENREF_41)). Chlorophyll fluorescence has many applications in plant diagnoses:

1. As a tool for selection of plants with different photosynthetic capacity for breeding purposes ([Bürling et al., 2010](#_ENREF_5); [Fracheboud et al., 1999](#_ENREF_16)).
2. As a tool to assess types of plant stress, e.g. extremes of temperature ([Dong et al., 2019](#_ENREF_11); [Haldimann et al., 2004](#_ENREF_19); [Sobrado, 2008](#_ENREF_54); [Wada et al., 2019](#_ENREF_61)), light ([Favaretto et al., 2011](#_ENREF_15); [Genty et al., 1989](#_ENREF_17); [Kalmatskaya et al., 2019](#_ENREF_30); [Tian et al., 2017](#_ENREF_58); [Zhang et al., 2019](#_ENREF_70)), water ([Doughty et al., 2019](#_ENREF_12); [Liu et al., 2018](#_ENREF_39); [Lu & Zhang, 1999](#_ENREF_41); [Nemeskéri & Helyes, 2019](#_ENREF_46); [Nemeskéri, Neményi, et al., 2019](#_ENREF_47); [Sánchez-Reinoso et al., 2019](#_ENREF_51); [Wada et al., 2019](#_ENREF_61); [Wang et al., 2018](#_ENREF_62)), salinity ([Alyemeni et al., 2018](#_ENREF_1); [Kalaji et al., 2011](#_ENREF_25); [Kalaji, Schansker, et al., 2014](#_ENREF_28); [Neocleous et al., 2008](#_ENREF_48)) and insect or pathological stresses ([Chávez-Arias et al., 2019](#_ENREF_8); [Huang et al., 2013](#_ENREF_22); [Wang et al., 2018](#_ENREF_62)) that can reduce the ability of a plant to perform optimally.
3. As a tool for nutrient status assessment ([Cartelat et al., 2005](#_ENREF_7); [Kalaji et al., 2018](#_ENREF_24); [Kalaji et al., 2016](#_ENREF_26); [Kalaji, Oukarroum, et al., 2014](#_ENREF_27); [Lu et al., 2001](#_ENREF_42); [Sitko et al., 2019](#_ENREF_53); [Wang et al., 2018](#_ENREF_62)).
4. As a trusted mechanism in estimating plant photosynthetic performance ([Baker et al., 2004](#_ENREF_2); [Wang et al., 2018](#_ENREF_62)).
5. As a tool in postharvest quality studies or assessments of horticultural and other crop plants ([Deell et al., 2003](#_ENREF_10)).

## 1.1 Chlorophyll Fluorescence Measurement

Chlorophyll fluorescence is measured by estimating the minimum level of fluorescence, it is usually made by the initial measurement in the non-attendance of photosynthetic light ([Maxwell et al., 2000](#_ENREF_43)). To utilize measurements of chlorophyll fluorescence to analyze photosynthesis, researchers must differentiate between non-photochemical quenching and photochemical quenching (heat dissipation). This is accomplished by halting photochemistry, which enables us to quantify fluorescence in the existence of non-photochemical quenching alone. To decrease photochemical quenching to minimum levels, a short flash of light with high intensity is used on the leaf. This temporarily shuts all PSII reaction centers, which prohibits the energy of PSII being passed to downstream electron carriers. Non-photochemical quenching will not be influenced if the flash of light is very short. During the flash, the fluorescence appears at the level of non-attendance of any photochemical quenching, known as maximum fluorescence Fm. ([Maxwell & Johnson, 2000](#_ENREF_43)).

The performance of photochemical quenching (which is a representation of the performance of PSII) can be evaluated by comparing Fm with the yield of fluorescence in the absence of photosynthetic light F0 and the steady yield of fluorescence in the light Ft. The performance of non-photochemical quenching is affected by multiple internal and external factors. A modification in heat scattering signifies changes in maximum fluorescence Fm. Heat scattering cannot be totally stopped, this implies that the yield of chlorophyll fluorescence in the non-attendance of non-photochemical quenching cannot be measured. Therefore, researchers used a dark-acclimatized point Fm′ in evaluations of non-photochemical quenching processes ([Maxwell & Johnson, 2000](#_ENREF_43)).

## 1.2 Chlorophyll fluorometers

There are many devices developed for chlorophyll fluorescence determination that exist and used. One of them is the lake model FV/FM, which measures maximum photochemical efficiency of PSII plants at a widespread and known as dark-acclimatized state([Baker & Oxborough, 2004](#_ENREF_2)), Y(II), an effective quantum yield of PSII photochemistry , Y(NYO), the quantum yield of regulatory energy dissipation in PSII, and Y(NO), the quantum yield of non-regulated energy dissipation in PSII ([Genty et al., 1989](#_ENREF_17); [Kramer et al., 2004](#_ENREF_38)). The puddle model is the older model for quenching protocol, which uses qP for estimation of photochemical quenching and NPQ for non-photochemical quenching ([Kooten et al., 1990](#_ENREF_36)). NPQ has also been revitalized to the lake model mathematically ([Guo et al., 2018](#_ENREF_18)), and ETR for electron transport rate ([Schreiber, 2004](#_ENREF_52)).

In this study, chlorophyll fluorescence measurements approaches were used to evaluate the best-LED light quality that produce strong seedlings of tomato cultivars based on its physiological performance.

# Material and Methods

All experiments were conducted in the LED light chambers at Fujian Agriculture and Forestry University, Fujian, China. The experimental system set up includes seven (7) chambers; Each Chamber has dimensions of 60 x 60 x 60 cm. Different LED light treatments for tomato cultivars were used in the range of 100 μmol.m−2.s−1 with different spectra. The details of these treatments are shown in Table 1 and Figure 1. Two cultivars of tomato (*Solanum lycopersicum var. Gangmu No.1(钢木1号)*) and (*Solanum lycopersicum var. Millennium (千禧)*) were sown in 32-cell cells plug trays (28 cm width × 54 cm length × 8 cm height. Luoxi Plastic Products Co., Shandong, China) that is filled with commercial growing substrate (N-P2O5- K2O ≥ 3%, Organic matter≥ 45% pH 5.5:6.5, Jiangping Enterprise Co., Fujian, China). One growth box per light spectrum containing one plug tray per cultivar was used. In total, 32 seeds were sown in each growth box per cultivar. During the growth, irrigation for seedlings was applied daily or as required. One week after sowing, seedlings started to receive fertilization based on water-soluble fertilizers (compound fertilizers "N-P2O5- K2O ≥ 54% 20:20:20+TE", Ruierkang Co., Russia, and Stimufol Amino (compound fertilizers “N 25%, P 16%, K 12%, Amino acids 2%, Boron 0.044%, Fe 0.17%, Molybdenum 0.001%, Zink 0.03%, Copper 0.085, Cobalt 0.01%, Mg 0.02%, Manga 0.085% and EDTA” Shoura Co., Egypt.) two times per week along with the irrigation.

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| Fig. 1. Spectrum distribution of the treatments light in the experiment. |

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| Table 1. LED light, light quality, light intensity, photoperiod, temperature and humidity used in the environments. | | | | | | | |
| Light Treatments | Light spectral ratios | Peak wave length  λp (nm) | light intensity (μmol.m-2.s-1) | Photoperiod  Light/Dark | Temperature (ºC) | | Relative humidity (%) |
| Day | Night |
| R | 100 | 662 | 100 ±2 | 12h /12h | 25 ± 2 | 20 ± 2 | 60 ± 10 |
| R7:B3 | 70:30 | 662 | 100 ±2 | 12h /12h | 25 ± 2 | 20 ± 2 | 60 ± 10 |
| R5:G2:B3 | 50:20:30 | 662 | 100 ±2 | 12h /12h | 25 ± 2 | 20 ± 2 | 60 ± 10 |
| R3:G2:B5 | 30:20:50 | 445 | 100 ±2 | 12h /12h | 25 ± 2 | 20 ± 2 | 60 ± 10 |
| R3:B7 | 30:70 | 445 | 100 ±2 | 12h /12h | 25 ± 2 | 20 ± 2 | 60 ± 10 |
| B | 100 | 445 | 100 ±2 | 12h /12h | 25 ± 2 | 20 ± 2 | 60 ± 10 |
| WFL | 100 | 544 | 100 ±2 | 12h /12h | 25 ± 2 | 20 ± 2 | 60 ± 10 |

## Data collection: Data were collected based on the following methods:

### Plant Growth characteristics

Data of growth parameters were collected 45 days after sowing (DAS). Plant height (cm) was measured using a ruler; it was measured from the base of the plant at soil surface to top of the plant. Stem diameter (mm) was measured using a digital Vernier caliper. Leaf area was determined according to the methodof ([Pandey et al., 2011](#_ENREF_50)), total leaf area (cm2) was calculated by the number of leaves **×** leaf area.

### Measurement of Photosynthetic Activity

Chlorophyll fluorescence was estimated by using a PAM 2500 chlorophyll fluorescence meter (Heinz Walz GmbH, Effeltrich, Germany). The fourth leaf from each plant was selected randomly for estimation. The leaf area of the standard measuring head is 1.3 cm2 and a saturated flash illumination from red LEDs (25000 μmol.m−2.s−1, 300 ms duration) was applied to determine the maximum chlorophyll fluorescence with closed PSII centers after dark acclimation (Fm) and during illumination (Fm'). Fluorescence induction kinetics was measured after dark adaptation for 30 min, then the rapid light curve (RLC) was recorded immediately. The steady-state fluorescence was measured after 20s of exposure to the light similar to the growth irradiance (100 μmol.m−2. s−1), the light intensity gradient of the RLC was (0, 1, 30, 63, 100, 140, 197, 362, 618, 784, and 1159 μmol.m−2. s−1).

Under dark and light conditions, the effective quantum yield of PSII photochemistry Y(II) ([Butler, 1978](#_ENREF_6)), the quantum yield of non-regulatory energy dissipation [Y(NO)=Fs/Fm] and the quantum yield of regulatory energy dissipation [Y(NPQ)=1–Y(II)–Y(NO)] were measured. Non-photochemical quenching (NPQ), photochemical quenching (qP) and the electron transport rate (ETR) were also measured. Measurements were conducted 4 replicates per treatment.

## Data analysis

The experiment was laid out in a completely randomized design with three replicates. All of the data were subjected to one-way analysis of variance (ANOVA). SPSS statistical software package version 16.0 (SPSS Inc., Chicago, IL, USA) was used for statistical analysis of the data. Significantly different means were separated using Duncan’s multiple range test at the P < 0.05 level of probability ([Duncan, 1955](#_ENREF_13)). All graphs were made using Excel 2007 (v12.0) using means and standard error for each data point.

# Results

## Plant Growth characteristics

Light quality with LEDs had significant effects on morphological appearances of tomato seedlings (Table 2, Fig. 2). The plant height of cultivars J and M under R5:G2:B3 and R7:B3 treatments were significantly lower and higher than other treatments respectively. Stem diameter of plants irradiated with R3:B7 was significantly larger than those under the other LED combinations and there was no significant difference among those under the irradiations of the other LEDs. Total Leaves area (cm2) of plants irradiated with R7:B3 had significantly larger area than those under more other LEDs except fort R5:G2:B3 and R.

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| Fig. 2. Tomato seedlings growth under diﬀerent LED lighting 40 days |

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| Table 2. Effect of LED light quality on plant growth characteristics of tomato seedlings Gangmu No.1 and Millennium cultivars. | | | | | | |
| Light Treatments | Gangmu No.1 | | | Millennium | | |
| Plant height  (cm) | Stem diameter (mm) | Total Leaves area (cm2) | Plant height  (cm) | Stem diameter (mm) | Total Leaves area (cm2) |
| **R** | **21.07±0.96 b** | **2.85±0.05 ab** | **123.67±7.17 d** | **22.00±0.29 b** | **2.66±0.05 b** | **71.33±10.74 d** |
| **R7:B3** | **24.33±0.33 a** | **3.05±0.19 ab** | **194.75±9.59 a** | **26.67±1.96 a** | **3.57±0.09 a** | **231.71±18.31 a** |
| **R5:G2:B3** | **17.67±0.72 c** | **2.96±0.23 ab** | **117.33±14.11 d** | **17.00±0.29 d** | **2.70±0.10 b** | **85.13±17.81 cd** |
| **R3:G2:B5** | **19.50±0.76 bc** | **3.10±0.11 ab** | **184.45±18.42 ab** | **19.00±0.58 cd** | **3.58±0.33 a** | **141.96±8.89 bc** |
| **R3:B7** | **21.00±0.58 b** | **3.26±0.19 a** | **176.27±16.28 a-c** | **23.00±0.76 b** | **3.75±0.36 a** | **203.81±9.27 ab** |
| **B** | **20.50±0.76 b** | **2.95±0.07 ab** | **143.27±15.98 b-d** | **23.17±0.60 b** | **3.24±0.16 ab** | **191.92±39.94 ab** |
| **WFL** | **18.00±0.58 c** | **2.63±0.18 b** | **134.87±7.96 cd** | **21.67±0.93 bc** | **2.69±0.12 b** | **159.41±9.06 b** |
| Values are means of three replicates. Different letters in the same column indicate significant differences according to Duncan’s multiple range test at P ≤ 0.05. | | | | | | |

## Chlorophyll fluorescence measurements

### Measurements under dark-acclimated samples

We measured the rapid light curves (RLCs) of dark-adapted and the results are shown in Figure 4. Dark-adaptation allows PSII reaction centers to open, electron transport chain to be oxidized, photoprotective mechanisms (Xanthophyll Cycle) and the trans-thylakoid to be relaxed and gradient to be depleted. The effective quantum yield of PSII photochemistry Y(II) decreased directly with stable light intensity of 100 μmol.m−2. s−1 at both light qualities in both cultivars, and then increased rapidly with continued exposure to light at both light qualities in both cultivars. The Y(II) under R3:G2:B5 was significantly higher than other treatments at 60-140 and 180-300 seconds in the J cultivar (Fig.3 J-1) , while in cultivar M, itwas significantly higher than other treatments at 40-300 seconds (Fig.3 M-1).

The quantum yield of regulated energy dissipation in PSII [Y(NPQ)] increased rapidly at both light qualities and cultivars. The [Y(NPQ)] in cultivar J was the highest under B, WFL and R3:B7 treatments at 60-100, 120-140 and 160-300 seconds respectively, (Fig.4 J-1), while in cultivar M, it was the highest under B and R3:G2:B5 treatments at 60-80, 140-300 seconds respectively, (Fig.4 M-1). The quantum yield of non-regulated energy dissipation in PSII [Y(NO)] increased rapidly when initially exposed to light and decreased directly at 40 seconds with increasing timeframe at all light qualities in both cultivars. The [Y(NO)] in cultivar J was the highest under R treatment at 60-300 seconds (Fig. 5 J-1), while in cultivar M, it was the highest under R treatment at 120-300 seconds (Fig. 5 M-1).

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| Fig. 3. Effects of LED light quality on RLC of the dark and light-adapted effective quantum yield of PSII photochemistry Y(II) in tomato leaves (J-1,M-1, J-2,M-2). Line markers indicate the average ± standard error (*P≤0.05*, n=4). |

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| Fig. 4. Effects of LED light quality on RLC of the dark and light-adapted quantum yield of regulatory energy dissipation in PSII Y(NPQ) in tomato leaves (J-1,M-1,J-2,M-2). Line markers indicate the average ± standard error (*P≤0.05*, n=4). |

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| Fig. 5. Effects of LED light quality on RLC of the dark and light-adapted quantum yield of non-regulated energy dissipation in PSII Y(NO) in tomato leaves (J-1,M-1,J-2,M-2). Line markers indicate the average ± standard error (*P≤0.05*, n=4). |

Non photochemical quenching (NPQ) increased rapidly with increased timeframe all light qualities in both cultivars. The (NPQ) in cultivar J was highest under B and R3:B7 treatments at 40-160 seconds and R7:B3, R3:B7, and Btreatments at 160-300 hours(Fig. 6 J-1), while in cultivar M, it was the highest under B at 40-120 seconds, R7:B3 at 140-160 seconds, R3:G2:B5 at 180-280 secondsand then B treatment at 300 seconds (Fig. 6 M-1). Photochemical quenching coefficient (qP) decreased directly with stable light intensity of 100 μmol.m−2. s−1 all light qualities in both cultivars then increased rapidly with continued exposure to light at both light qualities in both cultivars. The (qP) in (J) cultivar was the highest under R3:G2:B5,R5:G2:B3, and Bin cultivar J at 80-300 seconds(Fig. 7 J-1), while in cultivar M, it was highest under B and R7:B3 at 80-300 seconds (Fig. 7 M-1).

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| Fig. 6. Effects of LED light quality on RLC of dark and light-adapted non-photochemical quenching (NPQ) in tomato leaves (J-1,M-1,J-2,M-2). Line markers indicate the average ± standard error (*P≤0.05*, n=4). |

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| Fig. 7. Effects of LED light quality on RLC of dark and light-adapted photochemical quenching coefficient (qP) in tomato leaves (J-1,M-1,J-2,M-2). Line markers indicate the average ± standard error (*P≤0.05*, n=4). |

The electron transfer rate of PSII (ETR) increased rapidly with increase in exposure time at both light qualities in both cultivars. The ETR performed best under R3:G2:B5 in cultivar J (Fig. 8 J-1), while the best performance was observed under R7:B3 in cultivar M at 40-300 seconds (Fig. 8 M-1). The ETR in cultivar J was the highest under R3:G2:B5 treatment in cultivar J at 40-160 seconds then 200-300 seconds, there was no significant difference among all treatments except R at 40-140 seconds,R3:G2:B5, R7:B3, andR5:G2:B3 (Fig. 8 J-1), while in cultivar M, ETR was the highest under the R7:B3 treatments at 40-300 seconds (Fig. 8 M-1).

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| Fig. 8. Effects of LED light quality on RLC of dark and light-adapted electron transport ratio (ETR) in tomato leaves (J-1,M-1,J-2,M-2). Line markers indicate the average ± standard error (*P≤0.05*, n=4). |

### Measurements under light-acclimated samples

The rapid light curves (RLCs) of light-acclimated photosynthetic quantum yields for PSII were measured. The results showed that the photosynthetic electron transport activity was sensitive to spare light energy and significantly correlated to the oxidation state of electron transfer concatenation. The effective quantum yield of PSII photochemistry Y(II) had the best performance under R5:G2:B3 and WFL in both cultivars (Fig.3 J-2 and M-2). It decreased gradually with increasing light intensity at both light quality treatments. The Y(II) under R5:G2:B3 and R3:G2:B5 were significantly higher than others at almost all light intensities for cultivar J (Fig.3 J-2), while under WFLit was significantly higher than other treatments at almost all light intensities for cultivar M (Fig. 3 M-2).

The quantum yield of regulated energy dissipation in PSII [Y (NPQ)] had the best performance under B in both cultivars (Fig. 4 J-2 and M-2). It increased rapidly with increasing light intensity at both light qualities used in both cultivars with the highest being under B in cultivar J at almost all light intensities (Fig. 3 J-2). Nevertheless, it was statistically similar under all treatments except under R where it was lower in cultivar M (Fig. 4 M-2). The quantum yield of non-regulated energy dissipation in PSII [Y(NO)] had the best performance under R in both cultivars (Fig. 5 J-2 and M-2). It increased rapidly when initially exposed to light and stabilizes after slightly decreased. But it increases by increasing light intensity up to 63 μmol.m−2. s−1 at all light qualities in both cultivars. The Y(NO) was the highest under the R treatment in both cultivars at all light intensities (Fig. 5 J-2, M-2).

Non photochemical quenching (NPQ) had the best performance under B and R3:G2:B5 in both cultivars (Fig.6 J-2 and M-2). The (NPQ) increased gradually with increasing light intensity at all light qualities in both cultivars. The NPQ was significantly higher under Band R3:G2:B5 treatments compared to WFL at almost all light intensities in both cultivars (Fig.6 J-2 and M-2). The Photochemical quenching coefficient (qP) had the best performance under treatments R5:G2:B3 and WFL in both cultivars (Fig. 7 J-2 and M-2). It decreased gradually with increasing light intensity at all light qualities tested in both cultivars. The qP was significantly lower under R, R3:B7 and B compared to WFL at almost all light intensities in both cultivars (Fig.7 J-2 and M-2).

The electron transfer rate (ETR) of PSII performed better under R5:G2:B3 in cultivar J (Fig.8 J-2), while under the WFL in cultivar M, it performed best before the light intensity reached 270 μmol.m−2.s−1 and R3:G2:B5 after light intensity reached 270 μmol.m−2.s−1 (Fig.8 M-2). The ETR increased when the light intensity increases and it became steady when the light intensity reached 473, 618, 748 and 1159 μmol.m−2.s−1 depending on the treatments except R which declined after it reached 473 μmol.m−2.s−1 in both cultivars. The ETR of R5:G2:B3 was significantly higher than that of other treatments in cultivar J (Fig.8 J-2), while it was statistically similar under all other treatments at all light intensities except R where it was lower in cultivar M (Fig.8 M-2).

# Discussion

In general, the morphological and physiological characteristics of the plant are strongly affected by the quality of light ([Kalmatskaya et al., 2019](#_ENREF_30); [Whitelam et al., 2007](#_ENREF_64)). In this research, the interactions between photosynthesis and chlorophyll fluorescence parameters were exploited and how they are affected by light quality provided by LED light quality and fluorescent lamps. In this context, it was hypothesized that the efficiency of the process of photosynthesis and chlorophyll fluorescence parameters significantly affected the performance of tomato seedlings.

## Growth parameters

The process of photosynthesis in higher plants requires the interception of light and its utilization. The light trapped by the leaves is influenced by the wavelength, the intensity and angle of incidence ([Brodersen et al., 2010](#_ENREF_4)) as well as the total leaves area Gangmu No.1 and Millennium cultivars reacted strongly to R7:B3 not only in terms of total leaf area but also plant height as shown in Table 2. Similar results were obtained by [Yang et al. (2017)](#_ENREF_66) and [Kim et al. (2019)](#_ENREF_34), they observed a mixture of red and blue LED lights was favorable for total leaves area and plant height. In terms of stem diameter, Gangmu No.1 and Millennium cultivars reacted strongly under R3:B7. This result was in agreement of the findings of [Yang et al. (2017)](#_ENREF_66), [Naznin et al. (2019)](#_ENREF_45) and [Tang et al. (2019)](#_ENREF_57). For tomato seedlings, it showed that a mixture of red and blue LED light was effective on stem diameter ([Kim & Hwang, 2019](#_ENREF_34); [Yang et al., 2018](#_ENREF_65)).

## Chlorophyll fluorometers

Effects of LED light on RLC of dark-adapted reaction centers in tomato leaves were studied, RLC measurements were obtained through the application of 20 second stable light photosynthetically active radiation (PAR) at 100 μmol.m−2.s−1. Rapid light curve (RLC) measurements were obtained through exposing the seedlings to 20 seconds light and increasing the PAR (0, 30, 63, 100, 140, 197, 362, 618, 784, and 1159 μmol.m−2.s−1).

In the dark, all photosynthetic reaction centers of plants are open and can be excited, all electron acceptors are in the oxidized state and are able to accept more electrons. At that moment, a sudden increase in chlorophyll ﬂuorescence occurs followed by a slow decrease in the induced ﬂuorescence. This phenomenon was first observed by Kautsky in 1931, and it is known as Kautsky’s effect ([Kautsky et al., 1931](#_ENREF_33)). When plants are exposed to light, all photosynthetic reaction centers are closed, all electron acceptors are fully oxidized and cannot accept oxidized electrons ([Kalaji et al., 2017](#_ENREF_29)). The electron transport carrier’s activity is adjusted specifically by light. The specific spectrum of solar radiation can weaken the photosystems, especially PSII, causing extra photo inhibition ([Takahashi et al., 2010](#_ENREF_56); [Tikkanen et al., 2014](#_ENREF_59); [Zavafer, Cheah, et al., 2015](#_ENREF_68); [Zavafer, Chow, et al., 2015](#_ENREF_69)). In this study, the photosynthetic electron transport was significantly observed to be influenced by light qualities on tomato leaves. The combination of red and blue light, as well as white light, was more helpful to efficient photosynthesis process and performance in tomato leaves; these findings were in agreement with previous studies ([He et al., 2017](#_ENREF_20); [Wang et al., 2016](#_ENREF_63); [Yang et al., 2018](#_ENREF_65)).

These results indicated that the different light qualities of LED specifically regulated energy distribution, state transition, heat dissipation, cyclic electron transfer, and the activity of the photosynthetic electron transport chain. Light quality can directly impact the photochemical reaction during short-term lighting and indirectly impacts photosynthetic electron transport by adjusting multiple biochemical processes such as endogenous hormonal balance and metabolic reactions. In tomato leaves, the reaction centers were open, active and capable of accepting electrons, the effective photochemical quantum yield of photosystem II constantly is increasing with time (Fig.3 J-1 and M-1), while Y(II) was observed under light-acclimated exposures with increasing PAR (0, 30, 63, 100, 140, 197, 362, 618, 784, and 1159 μmol.m−2.s−1) in tomato leaves. The reaction centers were closed, and not excited, all electron acceptors are fully oxidized and cannot accept more oxidized electrons, thus Y(II) decreases with increase timeframe and PAR (Fig.3 J-2, M-2). Our findings were supported by that of [Yang et al. (2018)](#_ENREF_65).

The quantum yield of regulatory energy dissipation in PSII Y(NPQ) corresponds to the fraction of energy dissipated in the form of heat via the regulated photoprotective NPQ mechanism. When Y(II)’s value approaches zero at high quantum flux densities, high values of Y(NPQ) are the indications of high photoprotective capacity ([Klughammer et al., 2008](#_ENREF_35)). The results of this study showed that the difference between the values of Y(NPQ) under dark-acclimated and light-acclimated was significant. The best treatments with high photoprotective capacity and ability of plant to protect itself against damages by excess illumination in cultivar J were observed under B and R3:B7, while B and R3:G2:B5 in cultivar M(Fig.4 J-(1-2) and M-(1-2)), which were in agreement with the findings of ([Yang et al. (2018)](#_ENREF_65)).

The quantum yield of non-regulated energy dissipation in PSII Y(NO) reflects the fraction of energy that is passively dissipated in the form of heat and fluorescence, mainly due to closed PSII reaction centers. The high values of Y(NO) reflect the inability of a plant to protect itself against damages by excess illumination ([Klughammer & Schreiber, 2008](#_ENREF_35)). These results showed that the value of Y(NO) under dark-acclimated and light-acclimated decreased slowly. The inability of the seedlings to protect itself against damage by excess illumination in both cultivars was observed under R(Fig.5 J-(1-2) and M-(1-2))which is in tandem with the findings of [Yang et al. (2018)](#_ENREF_65).

In order to decrease photo damage, plants have devised several preventive mechanisms, including non-photochemical quenching (NPQ) which quenches the agitation of chlorophyll molecule within the light-harvesting antennae of PSII by converting excitation energy into thermal energy, which can then be sent out ([Kasajima et al., 2011](#_ENREF_32); [Zhao et al., 2017](#_ENREF_71)). According to one NPQ model ([Chávez-Arias et al., 2019](#_ENREF_8); [Zaks et al., 2012](#_ENREF_67)), rice leaves are often unable to utilize all the light absorbed by their photosynthetic pigments for CO2 fixation. A limited range for CO2 fixation limits photosynthetic electron transport, which then restricts the performance of the reaction centers of photosystem I (PSI) and PSII. In the case of PSII, these results leads to reactions that create harmful oxygens ([Long et al., 2015](#_ENREF_40)) as well as causing damage to the reaction center ([Evans et al., 2011](#_ENREF_14)) and membranes ([Davison et al., 2002](#_ENREF_9); [Nicol et al., 2019](#_ENREF_49)).

Additionally, under drought stress, a lower NPQ was observed when comparing drought-susceptible with drought-resistant plants. The photorespiration of drought-susceptible plants was significantly higher than that of drought-resistant plants ([Beis et al., 2012](#_ENREF_3)). It is known that the photorespiration process can disperse surplus equivalents of energy and decrease the generation of reactive oxygen species. It is also a source of H2O2 oxidization signal in the regulation of oxidization homeostasis. Generally, photorespiration is suggested as photoprotective mechanism important in reducing oxidative stress ([Kangasjärvi et al., 2012](#_ENREF_31); [Suzuki et al., 2012](#_ENREF_55); [Voss et al., 2013](#_ENREF_60)). There is likely to be cooperation or integration between photorespiratory metabolism and NPQ in order to keep oxidation homeostasis inside cells. Some other photoprotective mechanisms have been identified as closely related to NPQ, such as water-water cycle and cyclic electron transport and in organizing the induction of NPQ ([Johnson et al., 1994](#_ENREF_23); [Kramer et al., 2003](#_ENREF_37); [Miyake et al., 2005](#_ENREF_44)). The results showed that the value of NPQ under dark-acclimated and light-acclimated continuously increased with increasing time or increasing light intensity, the best combinations that dissipated excess reducing energy were R3:B7 and B in cultivar J and B and R3:G2:B5 in cultivar M after dark-acclimated (Fig.6 J-1 and M-1), while the best treatment dissipated excess reducing energy was B in cultivar J and R3:G2:B5 and B in cultivar M after light-acclimated (Fig.6 J-2 and M-2). These findings are supported by [He et al. (2017)](#_ENREF_20) and [Hoffmann et al. (2015)](#_ENREF_21).

Photochemical quenching (qP) is used as a parameter for estimating the fraction of PSII centers in open states based on a puddle model for the photosynthetic unit ([Kramer et al., 2004](#_ENREF_38)). qP was observed under dark-acclimated stable light PAR (100 μmol.m−2.s−1) in tomato leaves to be constantly increasing with time (Fig.7 J-1 and M-1), which indicated that the reaction centers increased in their work over time. On the other hand, qP under light-acclimated was observed to decrease with increase in PAR (0, 30, 63, 100, 140, 197, 362, 618, 784, and 1159 μmol.m−2.s−1) in tomato leaves and also decreased with time (Fig.7 J-2 and M-2), which indicated the reaction centers decreases with increasing photosynthetically active radiation. The best light combinations that helped keep as much as possible on the largest possible number of open reaction centers were R7:B3 and R3:G2:B5 in cultivar J and R7:B3 in cultivar M in dark-acclimated (Fig.7 J-1 and M-1), while the best light combinations that helped keep as much as possible the largest possible number of open reaction centers were R5:G2:B3 and R3:G2:B5 in cultivar J and R3:G2:B5 in cultivar M under light-acclimated (Fig.7 J-2 and M-2), which was supported by [He et al. (2017)](#_ENREF_20) and [Yang et al. (2018)](#_ENREF_65) .

Electron transport rate (ETR) is also a light-acclimated parameter that is directly correlated to Y(II) by the equation ETR = Y(II) × PAR × 0.84 × 0.5 and the relative estimation of ETR is achieved by adopting the procedure of [Schreiber (2004)](#_ENREF_52). The results showed that the value of ETR under dark-acclimated and light-acclimated were continuously increasing with increase in time or increasing light intensity. The best light combinations that increased electron transfer rate were R3:G2:B5 and R5:G2:B3 in cultivar J and R7:B3 in cultivar M in dark-acclimated (Fig.8 J-1 and M-1), while the best treatments that increased electron transfer rate in light-acclimated were R5:G2:B3 and R3:G2:B5 in cultivar J and R3:G2:B5 and WFL in cultivar M (Fig.8; J-2 and M-2), which was supported by ([Hoffmann et al. (2015)](#_ENREF_21)).

# Conclusion

Chlorophyll fluorescence can be used to asses types of plant stress, e.g. extremes of temperature, light, water, salinity and insect or pathological stresses that can reduce the ability of a plant to perform optimally. It can also be used to evaluate the performance of tomato seedlings during growth stages. In this study, one of the most important results obtained was that the parameters of chlorophyll fluorescence measured under dark-acclimation and light-acclimation did not change in all photosynthetic reaction centers significantly other than Y(II) and qP in both cultivars. Most of the light combinations containing a mixture of red and blue light were the best in effective quantum yield of PSII photochemistry (Y(II)), and electron transport rate (ETR) in both cultivars after dark-acclimated and light-acclimated. The variations among these characteristics suggested the linking morphological and physiological characteristics are insufficient to understand the effect of optical spectra on plant growth, so it is necessary to conduct molecular analysis and link them with morphological and physiological characteristics to know mechanisms of the effect of LED light on seedlings growth. In addition important to complete these treatments with seedlings until the production of the fruits.

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Authors of manuscript equally contributed in planning, execution, data collection, statistical analysis, draft development, commenting, revising and approving the manuscript for submission.

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