Alterations in growth, leaf chlorophyll fluorescence and thermoluminescence characteristics of perennial ryegrass (Lolium perenne L.) by different light intensity treatments

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Abstract

With the expeditious development of optoelectronics, the light-emitting diode (LED) technology as supplementary light has shown great effects to landscape plants. In urban areas, artificial lighting alters natural light conditions, potentially affecting plant performance. In current study, the six light intensities (100–600 μmol/(m^2•s)) and their effects on growth attributes, indices of chlorophyll fluorescence (CF) and thermoluminescence (TL) in seedlings of perennial ryegrass (*Lolium perenne L.*) was investigated. Results showed that moderate light intensity (300–400 μmol/(m^2•s)) enhanced germination, biomass accumulation, chlorophyll content, and photosynthetic efficiency, while higher and lower intensities (100 and 600 μmol/(m^2•s)) induced oxidative stress, reduced photosynthetic activity, and altered electron transport in photosystem II (PSII). CF analysis revealed impaired photochemical efficiency under higher and lower light, supported by decreased Fv/Fm and performance index (PI_{ABS}). TL measurements indicated disruptions in PSII charge recombination under stress, with the disappearance of the B band and emergence of the afterglow (AG) band. These findings suggested that perennial ryegrass thrives under moderate light but suffered photoinhibition and oxidative damage under extreme intensities, highlighting the need for optimized artificial lighting in urban green spaces.

1. Introduction

As the main energy source, light played a crucial role in plant physiology responding, influencing morphogenesis and subsequent growth (Dong et al., 2014; Xie et al., 2024). However, the use of artificial electric lighting was increased rapidly especially in urban area, which might change the process of plant physiology in modern time (Vialet-Chabrand et al., 2017). Excess light might induce the reactive oxygen species (ROS) forming and then the process of photoinhibition, which finally lead to an impaired plant growth and yield production (Krzemińska et al., 2015). Under severe conditions, photosynthetic electron transport through Photosystem II (PSII) was inhibited (Lebkuecher,1997). As a non-invasive yet powerful method, chlorophyll fluorescence (CF) analysis assessed photosynthetic electron transport, providing critical data on the photosynthetic apparatus's performance and structure for stress monitoring in plants (Stirbet et al., 2014; Živčák et al., 2014). Both the acceptor-side (Tourneux and Peltier, 1995) and donor-side of PS II (Chakir and Jensen, 1999) were regarded as a primary target of the higher or lower light intensity. Despite its notable advantages over chemiluminescence (CL) techniques, photosynthetic thermoluminescence (TL) was not yet widely adopted in this field. Nevertheless, it was proven that TL was a valuable tool for studying PS II photochemistry, particularly in assessing damage both on the acceptor and donor sides (Vass and Inoue, 1992; Vass et al., 1989). TL was an emission of light

occurring at characteristic temperatures when the preilluminated plant material is warmed up from low temperatures in dark (Lurie and Bertsch, 1974). The analysis of thermoluminescence glow curves enabled simultaneous evaluation of photosystem II functional states and oxidative stress conditions (Gilbert et al., 2004). At different temperatures under different conditions, there were more than seven TL components are emitted (Ducruet and Vass, 2009). Among TL components, the B band results from S□QB□/S□QB□ recombination which was emitting at around 30°C, and afterglow (AG) band emitted at around 45°C which represented a B-type recombination involving on the back transfer of electrons from stroma to the acceptor side of PS II (Ducruet, 2003; Wessels et al., 1976).

Perennial ryegrass as one of the most important grasses that was widely used as forage crop to produce high proportion of milk or meat and turfgrass species to make lawns, playground and golf courses of urban green areas (Foito et al., 2009; Dąbrowski et al., 2016). The ecological benefits of urban greenery extended to human health, as aesthetically pleasing lawns simultaneously improve a city's appearance and environmental conditions (Dąbrowski et al., 2017). As an urban turfgrass species, perennial ryegrass responded to both natural sunlight and artificial light sources. This necessitated a sensitive regulatory system to maintain balanced photosynthetic light reactions and coordinate subsequent metabolic processes (Yamori et al., 2016). At present, there were many studies on perennial ryegrass, mainly focusing on the accumulating heavy metals in its biomass and revegetation of metalliferous wastes of it but the research of which was rarely reported to be affected by urban light intensity (Bai et al., 2015; Arienzo et al., 2004). Therefore, this study examined artificial light effects on perennial ryegrass through controlled experiments with six light intensities, analyzing growth parameters, physiological traits, and chlorophyll fluorescence (CF) and thermoluminescence (TL) leaf characteristics.

2. Material and Methods

2.1 Plant material

'The Peak' (from Hotlandb arenbrug), a perennial ryegrass (*Lolium perenne L.*) characterized by low growth, tufted, hairless morphology, and a bunching habit, was used in the experiment.

Statement

All experimental procedures and field investigations involving this plant material were conducted in full compliance with relevant institutional policies, national legislation, and international guidelines.

2.2 Environmental conditions and experimental layout

The experiment was conducted in three intelligent plant growth chambers (FS130, Brno, Czech Republic) under the following conditions: a 16h photoperiod, day/night temperatures of 25/15°C, at 400 µmol/(m^2•s) photosynthetically active radiation (PAR), and 60% relative humidity. Using pots (20 cm × 20 cm; height × diameter) cultivated the plants containing 2.0 kg of a 1:1 (v/v) field topsoil-flower soil mix. This growing medium had an organic matter content of 11.56 g/kg, total N of 1.43 g/kg, total P of 1.68 g/kg, K of 233 mg/kg, S of 19 mg/kg, and a pH of 7.1. Seeds were surface-sterilized by soaking in 0.1% $HgCl_2$ for 10 minutes, with subsequent thorough rinsing (three times) in distilled water. On March 16, 2023, a total of 500 seeds were sown per pot in a substrate at 80% field capacity. The experimental layout comprised six light intensity treatments (100, 200, 300, 400, 500, and 600 µmol/(m^2•s)) with four replicates each.

2.3 Growth characters measurements

Germinated seeds and leaf length were measured per pot at the Day 3rd to Day 7th. From the germination day to Day 7th, 10 plants per pot were chosen randomly and cut to measure the leaf length (LL, cm). Leaf weight (LW, g/10 plants), root length (RL, cm) and root weight (RW, g/10 plants) was also measured at Day 7th. The germination potentiality, germination rate, germination index (Gi) and vigor index (Vi) was also calculated as Eq. (1–4) (Wiese and Binning, 1987).

$$\text{Germination potentiality (\%)} = \frac{\text{Numbers of germinated seeds at 3rd day}}{500} \times 100\% \quad (1)$$

$$\text{Germination rate (\%)} = \frac{\text{Numbers of germinated seeds at 7th day}}{500} \times 100\% \quad (2)$$

$$\text{Germination index } (G_i) = \sum \left(Gt/Dt\right) \quad (3)$$

$$\text{Vigor index } (V_i) = G_i \times \text{ leaf length (cm)} \quad (4)$$

Where Dt and Gt are the Day t and numbers of germination at Day t.

2.4 Physiological characters measurements

At day 22nd to day 28th, a DR6000 spectrophotometer (Hach, USA) was used to measure leaf soluble carbohydrate concentrations (SC) at 620nm by Anthrone method (Jermyn, 1975), leaf soluble protein concentrations (SP) at 595 nm by Coomassie Brilliant Blue (CBB) method (Bradford, 1976), leaf chlorophyll a (Chl a) and chlorophyll b (Chl b) concentrations at 645, 663 nm according to Litchtenthaler (1983) (Litchtenthaler and Wellburn, 1983), leaf malondialdehyde concentrations (MDA) at 532nm, 600nm and

450nm by Thiobarbituric acid method (TBA) (Draper et al., 1993) and leaf peroxidase activity (POD) at 470 nm by Guaiacol method (Kronfuss et al., 1996).

2.5 Heat stability measurement

Leaf heat stability was measured by the PlanTherm PT100 (Photon Systems Instruments, Brno, Czech Republic) to get the conductivity-temperature curve (Conductivity curve), using which to determine the threshold temperature (Conduct Critical Point, T_CC, °C) of the leakage of ions from cells. The heat stability of primary photosynthetic processes was evaluated by simultaneously detecting chlorophyll fluorescence intensity (T_CF, °C) in leaf material during heating.

2.6 Chlorophyll fluorescence parameter measurements

Plants were dark-adapted for 20 minutes before measurements. The following chlorophyll fluorescence parameters were recorded using a handheld FluorPen FP 100 MAX fluorometer (Photon Systems Instruments, Brno, Czech Republic). the parameters and meaning were shown in Table 1 (Lu et al., 2003). Transient curves were normalized as relative variable fluorescence (Eq. 5) (Kalaji et al., 2014).

Table 1
Parameters of chlorophyll fluorescence

Parameters and Formula		Meaning
Basic parameters	F_0	minimum fluorescence
	F_m, F_P	maximum fluorescence
	$F_v=F_m-F_0$	variable fluorescence
	F_v/F_m	variable to maximum fluorescence ratio
	${}_nF_v=F_v/F_0$	variable to initial fluorescence ratio (normalized variable fluorescence
Reaction center energy fluxes	ABS/RC	absorbed energy per PSII reaction center
	TR_0/RC	captured energy for reduction of Q_A (the primary electron acceptor in Photosystem II)
	ET_0/RC	captured energy for electron transport per PSII reaction center
	DI_0/RC	the amount energy consumed per active reaction center
Photochemical parameters	M	initial slope
	$PI_{ABS}= RC/ABS• \varphi P_0 /(1- \varphi P_0)• \psi_0 /(1- \psi_0)$	absorption basis

$V_t=(F_t-F_0)/(F_m-F_0)$ (5)

2.7 Photosynthetic Thermoluminescence (TL)

Take the appropriate size of the leaf sample, put the sample on the measuring pan and close the measuring chamber, then run the experiment to get the TL signal using the Thermoluminescence System TL 400/xx (Photon Systems Instruments, Brno, Czech Republic). TL emission was recorded while warming samples

from 0 to 70 ℃ at a heating rate of 0.5 ℃/s. Referring to Ducruet’s research, the TL bands were observed in photosynthetic leaves, T_m and origin correspond to a 0.5°C/s TL heating rate (Ducruet, 2009).

2.8 Statistical analysis of data

Data were analyzed by one-way ANOVA using SPSS v25.0 (SPSS software version 25.0, Chicago, Illinois, USA). Significant differences were identified by Tukey's HSD test ($P <$

0.05). The Redundancy analysis (RDA) with covariance matrices in CANOCO 5.0 (Microcomputer Power, Inc., Ithaca, NY) evaluated interrelationships among growth traits, leaf chlorophyll concentrations, and fluorescence parameters. Inter-parameter correlations were quantified through Pearson's simple correlation analysis implemented in the SPSS statistical package.

3. Results

3.1 Light intensity effect on perennial ryegrass growth and physiological characters

Germination started within 3 days and completed on the7th day. Seed germination delayed as the higher light intensity (Fig. 1a). The variance of results revealed that significant differences among the different light intensity for germination rate, potentiality, Gi, Vi on perennial ryegrass (Fig. 1a) and Vi was strongly affected by light intensity ($F = 50.44$, $P < 0.01$). A continuous increase in length of leaf and root was detected in 300 and 400μmol/(m^2•s) (Fig. 1b). The highest light intensity (600 μmol/(m·s)) significantly reduced both leaf and root size. The decline in leaf length (LL) was greater and more statistically significant ($F = 47.39$, $P < 0.01$) compared to that of roots ($F = 40.19$, $P < 0.01$) with higher light intensity. Among the fresh weight of leaf and root, highly significant differences were observed under 6 light intensity ($F = 28.01$ and 11.58, respectively; $P < 0.01$) (Fig. 1b). Leaf fresh weight (LW) was significantly reduced by the higher light intensity (600μmol/(m^2•s)) whereas root fresh weight (RW) was reduced under lower light intensity (100μmol/(m^2•s)).

The leaf chlorophyll concentrations were summarized in Table 2 and all the lighting treatments showed significant differences. The data indicated that there was a considerable decrease of Chl a concentration after higher light intensity (30.99% at 600μmol/(m^2•s) below at the 300μmol/(m^2•s)) and the Chl b concentration at 100μmol/(m^2•s) was 25.93% lower than that at 300μmol/(m^2•s). Effects of lighting after one month on SP concentration was greater for 300μmol/(m^2•s) (Table 2) and the responses of leaf SC to the treatments was also significant and also have light intensity effect. The highest MDA concentration at 600μmol/(m^2•s) while the lowest POD was at that light intensity.

Table 2
Alternation of light intensity on perennial ryegrass leaf physiological characters

Treatments (μmol/(m^2•s))	Chlorophyll a (Chl a, mg/g FW)	Chlorophyll b (Chl b, mg/g FW)	Chl (a + b) (mg/g FW)	Chl a/b
100	0.66 ± 0.01b	0.18 ± 0.01d	0.84 ± 0.01c	3.60 ± 0.09a
200	0.70 ± 0.01a	0.25 ± 0.01b	0.95 ± 0.01b	2.82 ± 0.10b
300	0.71 ± 0.01a	0.27 ± 0.01a	0.98 ± 0.01a	2.63 ± 0.06c
400	0.56 ± 0.01c	0.27 ± 0.01a	0.83 ± 0.01c	2.10 ± 0.03f
500	0.55 ± 0.01c	0.25 ± 0.01b	0.80 ± 0.01d	2.17 ± 0.04e
600	0.49 ± 0.01d	0.20 ± 0.01c	0.79 ± 0.01d	2.50 ± 0.06d
F value	3602.22**	145.29**	1179.36**	198.47**
Treatments (μmol/(m^2•s))	Soluble carbohydrate concentration (SC, mg/g FW)	Soluble protein concentration (SP, mg/g FW)	Malondialdehyde concentration (MDA, mmol/g FW)	Peroxidase activity (POD, Units/g·min FW)
100	2.34 ± 0.02c	5.76 ± 004c	8.70 ± 1.77b	142.67 ± 11.61d
200	2.41 ± 0.03c	7.37 ± 0.07b	4.72 ± 0.20c	223.73 ± 4.89c
300	3.14 ± 0.01a	8.24 ± 0.08a	1.18 ± 0.47e	323.73 ± 40.41a
400	2.73 ± 0.08b	8.16 ± 0.13a	2.50 ± 0.66d	273.60 ± 22.53b
500	1.82 ± 0.09d	5.49 ± 0.12d	4.43 ± 1.84c	98.13 ± 16.86e
600	1.95 ± 0.03d	5.75 ± 0.13c	11.34 ± 1.81a	58.13 ± 21.60f
F value	713.75**	484.85**	25.32**	63.74**

The values presented in each column of table are mean ± standard deviation. The last part of table means the F value. ns, not significant; * $P < 0.05$; ** $P < 0.01$.

3.2 Light intensity effect on leaf heat stability of perennial ryegrass

Figure 2 (b) to (g) showed the curves of conductivity (μS/cm) and fluorescence (Ft) signal (relative units) vs. temperature under 6 light intensity conditions. The maximum curvature point temperature of the conductivity curve (T_CC) and the chlorophyll fluorescence curve

($T_C F$) were calculated by the points of curvature curve which was showed in Fig. 1 (a). $T_C C$ and $T_C F$ all had significant different under 6 treatments ($F = 217.17$, 6.70, respectively; $P < 0.01$) while the highest temperature was 60.88°C for $T_C C$ under 300μmol/(m^2•s) and 42.48°C for $T_C F$ also under 300μmol/(m^2•s).

3.3 Light intensity effect on leaf chlorophyll fluorescence parameters (CF) and O-J-I-P test of perennial ryegrass

The effects of different lighting intensities on values of chlorophyll fluorescence parameters were shown in Table 3. The results indicated that F_0, F_m and F_v decreased fast under 600μmol/(m^2•s) and also had significant lighting effect. In regard to the F_v/F_0($_nF_v$), it showed an significant decrease under 100μmol/(m^2•s) light intensity. Under 6 different lighting intensities, there were significant differences of F_v/F_m; moreover, the average value of F_v/F_m was the highest in the leaf of 300μmol/(m^2•s) light intensity. M_0 did not have significantly change by the lighting treatments, and values of PI_{ABS} parameter derived from CF parameters confirmed a much higher responsiveness of PI_{ABS} compared to F_v/F_m. PI_{ABS} was significantly decreased by the light intensity ($F = 5.47$, $P < 0.01$) and the lowest of it was under 600μmol/(m^2•s) light intensity.

Table 3
Alternation of light intensity on perennial ryegrass leaf chlorophyll fluorescence parameters

Treatments	Leaf chlorophyll fluorescence intensity (relative unit)					
($\mu mol/(m^2 \bullet s)$)	F_0	F_m	F_v	$F_v/F_0(nF_v)$	F_v/F_m	M_0
100	5768 ± 58bc	22744 ± 804bc	16977 ± 434bc	2.94 ± 0.10c	0.75 ± 0.01c	0.87 ± 0.08
200	6390 ± 642ab	28797 ± 3309ab	22407 ± 2669ab	3.49 ± 0.12abc	0.78 ± 0.01ab	0.92 ± 0.05
300	7096 ± 814a	34974 ± 3434a	27878 ± 3040a	3.92 ± 0.58a	0.79 ± 0.02a	0.95 ± 0.09
400	5958 ± 607abc	27501 ± 2885bc	21544 ± 2582abc	3.60 ± 0.50ab	0.78 ± 0.02ab	1.13 ± 0.18
500	6001 ± 743abc	25066 ± 1699bc	19064 ± 1272bc	3.18 ± 0.04bc	0.76 ± 0.01bc	0.92 ± 0.10
600	4757 ± 440c	20182 ± 628c	15425 ± 447c	3.25 ± 0.24bc	0.76 ± 0.01bc	0.90 ± 0.04
F value	3.53*	4.66*	4.69*	3.23*	3.87*	2.47ns
Treatments	O-J-I-P test parameters (relative unit)					
($\mu mol/(m^2 \bullet s)$)	PI_{ABS}	ABS/RC	TR_0/RC	ET_0/RC	DI_0/RC	
100	1.51 ± 0.18a	2.85 ± 0.08ab	2.04 ± 0.04cd	1.17 ± 0.07ab	0.66 ± 0.01b	
200	1.74 ± 0.30a	2.62 ± 0.18bc	2.19 ± 0.08ab	1.21 ± 0.07a	0.58 ± 0.05b	
300	1.83 ± 0.15a	2.70 ± 0.06bc	2.25 ± 0.11a	1.22 ± 0.07a	0.58 ± 0.01b	
400	1.57 ± 0.22a	3.08 ± 0.25a	2.10 ± 0.06bc	1.12 ± 0.07abc	0.59 ± 0.02b	
500	1.44 ± 0.24a	2.62 ± 0.14bc	2.00 ± 0.10cd	1.08 ± 0.01bc	0.63 ± 0.04b	
600	0.83 ± 0.39b	2.57 ± 0.07c	1.94 ± 0.04d	1.03 ± 0.03c	0.89 ± 0.19a	
F value	5.47**	5.11**	6.86**	4.88*	6.35**	

The values presented in each column of table are mean ± standard deviation. The last part of table means the F value. ns, not significant; * $P < 0.05$; ** $P < 0.01$.

The partitioning of absorbed light energy *via* photochemical reaction center (RC) and thermal dissipation were also determined. The change of parameters including ABS/RC,

TR_0/RC, ET_0/RC, DI_0/RC were shown in Table 3. The light absorption per residue active RC (ABS/RC) was higher under 400μmol/(m^2•s) light intensity than that under 600μmol/(m^2•s) lighting. Moreover, the values of TR_0/RC and ET_0/RC under 300μmol/(m^2•s) light intensity were both higher than that under 600μmol/(m^2•s) lighting. DI_0/RC (dissipated energy flux per PSII RC) increased under 600μmol/(m^2•s) light intensity, meaning more dissipation of excess excitation energy in these chloroplasts (Wang et al., 2018; Roosta et al., 2018).

The Fig. 3 showed the O-J-I-P test curves. The OJIP curves were sensitive to light intensity, as shown in Fig. 3(a). Increasing light intensity altered chlorophyll fluorescence, shifting the curve upward at 300μmol/(m^2•s) while at 600μmol/(m^2•s) and 100μmol/(m^2•s) lighting intensities which was a little different. Normalizing the relative variable fluorescence showed in Fig. 3 (b). There were two distinct trends: the increase in the J band (2 ms)) and the increase in the I band (30 ms). The increased J band and I band were more clearly visible under 300 or 400μmol/(m^2•s) light intensity than under those highest and lowest lighting intensities (He et al., 2018).

3.4 Light intensity effect on leaf photosynthetic thermoluminescence (TL) of perennial ryegrass

After different light intensity illumination, two major TL bands were observed (Fig. 4(a)) with peak locations around + 30°C (B band) and + 45°C (AG band), while their exact locations being dependent upon the treatments. For B band, lighting at 300 and 400μmol/(m^2•s) had the higher signal of TL than that at 200μmol/(m^2•s). Lighting at 600μmol/(m^2•s) had significant effect on the maximum temperature and also it strongly decreased the AG band intensity. Under 6 light intensity treatments, the curve was simulated of the maximum temperatures of TL curve, the equation was showed in Fig. 4(b), and R^2 was 0.96, extremely significant (Sane et al., 1996).

3.5 Correlation among growth, leaf physiological characters, chlorophyll fluorescence and TL parameters

The correlations among parameters were shown in Fig. 5. There were significant positive correlations between plant growth parameters (LL, RL, LW and RW) and leaf physiological parameters (SP, Chla, Chlb, T_CC and T_CF) except MDA and POD while the correlation with them was significant negative (Fig. 5(a)). The plant growth characters showed significant positive correlations with some CF parameters (F_v/F_m and F_v/F_0), but which were negatively correlated with TL.

The Redundancy Analysis (RDA) ordination of plots, based on plant physiological traits and leaf chlorophyll fluorescence (CF) or thermal leaf (TL) parameters, confirmed their interrelationships (Fig. 5(b)). The redundancy analysis (RDA) yielded significant results for all axes (pseudo-$F = 4.08$, $P = 0.006$). Leaf chlorophyll concentrations and SP together with leaf CF parameters and leaf heat stability ($T_C C$ and $T_C F$) were positively related to this axis. On the opposing side, SC, POD, MDA, and TL showed a negative correlation along this axis.

4. Discussions

4.1 Plant growth and physiology

The growth and physiological characters of plants were influenced by some main environmental factors such as light (Muneer et al., 2014) which included light intensity, light quality and light time (Wang et al., 2016b). Among these light characters, light intensity was the key factor for plant growth and also an essential source for photosynthetic activity (Singh and Singh, 2015; Fan et al., 2013). With the artificial lighting using in the city (including streetlights, buildings, vehicles and so on) (Gaston et al., 2017), it changed the light intensity. To cope with these situations, different urban plants might develop numerous morphological and physiological adaptations and each plant had its own optimal light intensity (Fan et al. 2013). In our study, the best germination and growth characters of perennial ryegrass was seen under 300 or 400μmol/(m^2•s) (Fig. 1). Relative to optimal light conditions, sustained low light exposure may restrict stoma opening in plants, consequently impairing leaf and root development. Conversely, excessive light intensity disrupted normal biosynthesis, diminishing assimilate translocation to both roots and leaves, thereby inhibiting proper biomass development (reduced root and leaf mass accumulation) (Matos et al., 2009; Gassmann, 2004).

The chlorophyll was some of the most important internal factors, whose concentrations in certain circumstances were able to restrict the photosynthesis (Brenda, 2001). In our study, the chlorophyll concentrations and ratio of ryegrass leaves showed significant variation under different light intensity (Table 2). The medium light intensity (300μmol/(m^2•s)) promoted higher Chl a, Chl b and Chl a + b concentrations that might be related to the light absorption capacity maximizing under the suitable light treatments (Zhang et al., 2015). However, the light intensity at 100 or 600μmol/(m^2•s) decreased Chl a and Chl b concentrations but increased the Chl a/b which might be related to chlorophyll disorganization by low or excess light (Griffin et al., 2004). The results also suggested that the photooxidative stress damage the photosystems and of leaves which made the reduction of the Chl a or Chl b concentrations (Chen et al., 2017). Soluble protein (SP) and soluble carbohydrate (SC) concentrations were crucial substances relating to the

osmoregulation of plants (Xi et al., 2013). In present study, SP and SC increased by optimal light intensity. This result was consistent with some other plants that SP or SC serve as osmoprotective compounds in multiple plant species, contributing to turgid maintenance, membrane stabilization, and protection against stress-related deterioration (Feng et al., 2014).

Under high or low light stress, plants could enhance their defense mechanisms by upregulating antioxidant biosynthesis, enabling osmotic adjustment to mitigate ROS (e.g., H_2O_2 and O_2^-) accumulation(Wang et al., 2016a). Under these conditions, the balance between ROS production and scavenging was perturbed, leading to lipid peroxidation (Cao et al., 2018), cellular membrane damage, and metabolic dysfunction, ultimately inducing oxidative stress through peroxide accumulation (Yu et al., 2016). As the main byproduct of lipid peroxidation, MDA levels reflected the extent of oxidative membrane damage and the adaptation of plant facing to stress. The membrane protective enzyme, such as POD was the major component of plant enzymes involved in defense responses. The enzyme activities reflected the adaptability of plant to environmental stress (AliEun-Joo and Paek, 2005). In our study, when light intensity from 100μmol/m^2s reached 600 μmol/m^2s, the activity of POD initially increased and then decreased drastically to very low levels (Lu et al., 2017). Under higher light intensity plant developed various defense systems formed ROS caused to protect stress damage and make higher POD activity. Conversely, a sustained increase in MDA concentration was observed under high light intensity (600 μmol/m□s), indicating that the photosynthetic apparatus was subjected to severe light stress, thereby provoking photoinhibition. (Table 2) (Fu et al., 2012). Perhaps because the higher light intensity enhanced lipid peroxidation, consequently leading to an accumulation of MDA (malondialdehyde) in plants (Zhou et al., 1999).

4.2 Leaf CF and TL

The current study had been shown that the incident light intensity could change the leaf photosynthetic apparatus and the proper range of it could promote the development of photosynthetic apparatus (Ghorbanzadeh et al., 2021). CF as a tool was developed, which could measure photosynthetic efficiency and detected some stresses that harmed the photosynthetic apparatus (Legendre et al., 2021). Our results demonstrated that the variation pattern of F_v/F_0 (potential activity of PSII) was similar to that of F_v/F_m (the maximal photochemistry efficiency of PSII), however it were notably more pronounced during light treatment. The results illuminated that higher or lower light intensity as a stress all affected CF system. Under the higher light intensity 600 μmol/(m^2•s), the F_v/F_m and F_v/F_o was decreased indicating the occurrence of photoinhibition (Table 3), which was accordance with the results of Hao et al. (2021). Lowest F_v/F_m and F_v/F_0 was under the light intensity 100 μmol/(m^2•s) might be implied the damage of the PSII reaction center

(Ding et al., 2013). M_0 served as an indicator of QA deoxidation kinetics and the QA-accumulation level, simultaneously reflecting electron transport activity from QA to QB (the secondary PSII electron acceptor) (Srivastava et al., 1997). Under 400μmol/(m^2•s) light intensity the M_0 was the highest indicating that more efficient electron flow of leaf from QA to QB, thereby decreasing Q_A^- accumulation and enhancing photochemical reaction effectiveness (Table 3). PI_{ABS} as the performance index of PS II was shown to respond rapidly to different light intensities. The highest light intensity 600μmol/(m^2•s) decreased the PI_{ABS} significantly (Table 3) which mean the sample vitality was decreased (Mehta et al., 2010).

In our study, the normal OJIP transient curves showed higher and lower light-induced decrease in leaves, and it also showed consistent curve trend across all studied light conditions (Fig. 3a). While some researchers had been not solely analyzed the normal CF parameters but additionally using relative variable fluorescence and normalized differential parameters, which had shown promise identifying light intensities (Xia et al., 2019). The results indicated that suboptimal light intensities (both high and low) compromised the efficiency of photosynthetic electron transport, particularly during the J-I and I-P phases (Fig. 3b). The fluorescence intensity at the J and I time points determined the efficiency of electron transfer through the subsequent phases of the photosynthetic chain (Wang et al., 2018). In O-J phase the limitation arose from the exchange process between a reduced and an oxidized plastoquinone molecule at the Q_B site, in J-I phase it came from the reoxidation of plastoquinol and in I-P phase it came from the PSI acceptor pool (Schansker et al., 2005). The CF intensity changing in O-J and J-I phase represented the photosynthetic electron transport chain (PETC) activity from Q_A to Q_B and Q_B to PSI acceptor (Wang et al., 2012). Our results showed that high or low light intensities could affect the leaf electron transport especially from Q_B to PSI acceptor. Under the applied light intensities, a coordinated increase in ABS/RC, TR_0/RC, ET_0/RC, and DI_0/RC was observed in perennial ryegrass leaves (Table 3). This suggested that the PSII apparatus maintained homeostasis in energy flux—from initial absorption and trapping to electron transport—by modulating the numbers of active reaction centers (Wang et al., 2010). Our result was consistent with the former findings, where high or low light intensity treatment as a stress, the plants maintained a relative low electron transfer efficiency in PS II as a mitigated strategy (Sun et al., 2017). The DI_0/RC was the highest under 600μmol/(m^2•s) which mean more energy per active reaction center was consumed and the electron transfer efficiency was lower in PS II.

Thermoluminescence (TL) bands were routinely employed to investigate stress-induced alterations in chloroplasts and to assess the impact of exogenous compounds on electron transport processes within thylakoid membranes (Ducruet, 2003). In our research, under

low or high light intensities, the B band disappeared and the AG band appeared. This could be explained by the induction of proton leakiness of stressed thylakoids and or by the state of the reducing pool in chloroplasts (Krieger et al., 1998a). Most TL bands were predominantly generated by the thermally activated recombination of charges between the donor and acceptor sides of Photosystem II (PSII) (Skotnica et al., 2003). In our study, the appearance of the B band ($S_{2/3}Q_B^-$ recombination), was driven by the recombination between positive charges on S_2 and S_3 states of oxygen evolving complex (OEX) and negative charges on quinone acceptors Q_B (Krieger et al., 1998b). The AG band emerged due to impaired electron transfer from Q_A to Q_B under stress. This phenomenon was attributed to the recombination of $S_{2/3}Q_B^-$ charge pairs in PSII, triggered by reverse electron flow from stromal reductants through plastoquinone (PQ) to the Q_B site in reaction centers stabilized in the $S_{2/3}Q_B$ state. This mechanism was further associated with the accumulation of high cellular concentrations of ATP and/or NADPH (Belatik et al., 2012).

5. Conclusions

This study demonstrated that light intensity significantly influenced the growth, physiological responses, and photosynthetic performance of perennial ryegrass. Optimal light conditions (300–400 μmol/(m□·s)) promoted seed germination, biomass production, chlorophyll synthesis, and photosynthetic efficiency, while both low (100 μmol/(m□·s)) and high (600 μmol/(m□·s)) light intensities induced stress responses, including reduced photosynthetic activity, increased lipid peroxidation, and impaired electron transport in PSII. Chlorophyll fluorescence and thermoluminescence analyses provided insights into the underlying mechanisms, revealing photoinhibition and altered charge recombination under stress conditions. The findings underscore the importance of maintaining appropriate light intensities in urban environments to sustain healthy turfgrass growth and ecosystem services. Future studies should explore adaptive strategies to mitigate light stress and optimize artificial lighting for urban green spaces.

Declarations

Declaration of Competing Interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

All data generated or analyzed during this study are included in this published article.

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Figures

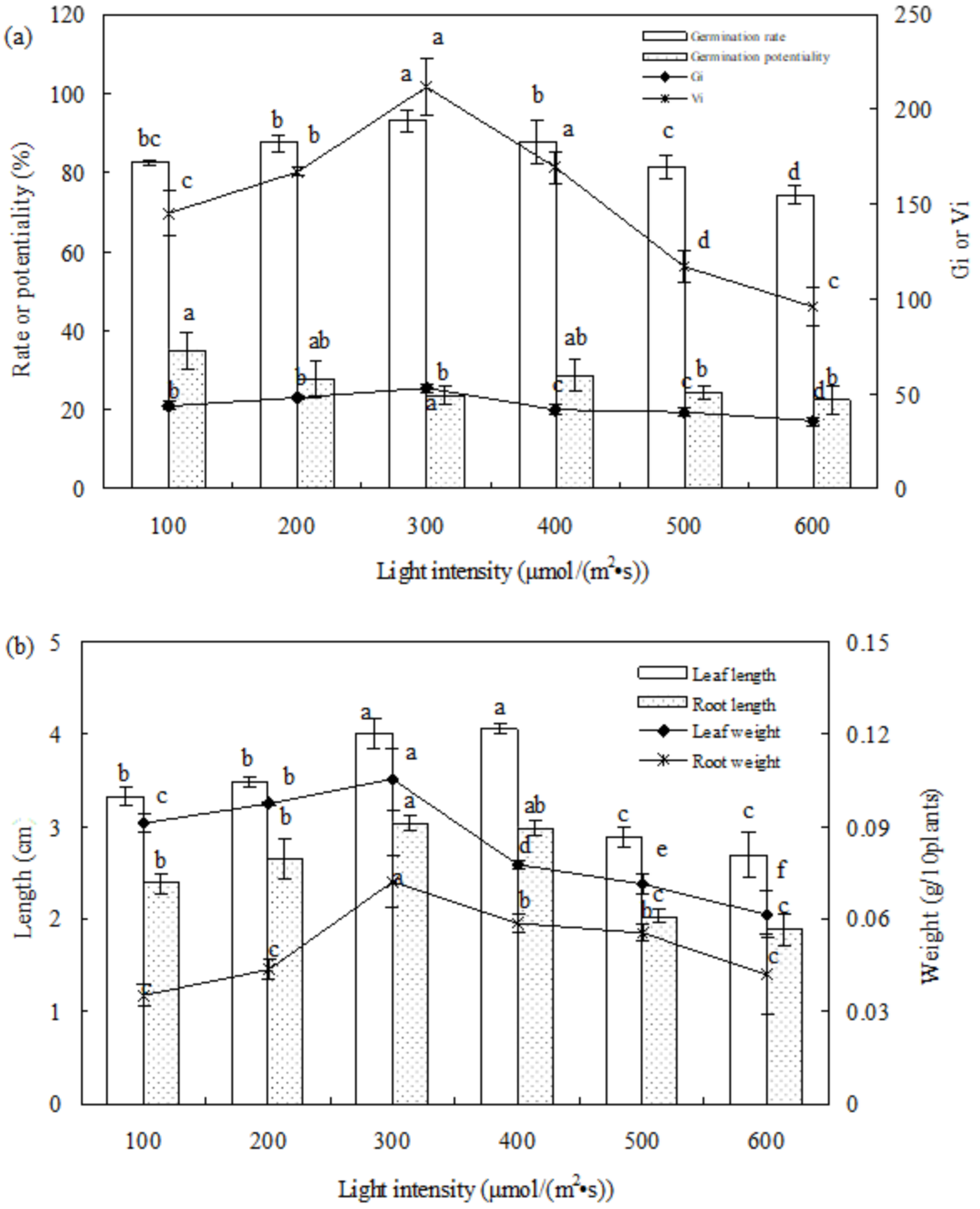

Figure 1

Light intensity effect on perennial ryegrass growth. (a): Light intensity effect on germination rate or potentiality and Gi or Vi; (b): Light intensity effect on leaf length and weight.

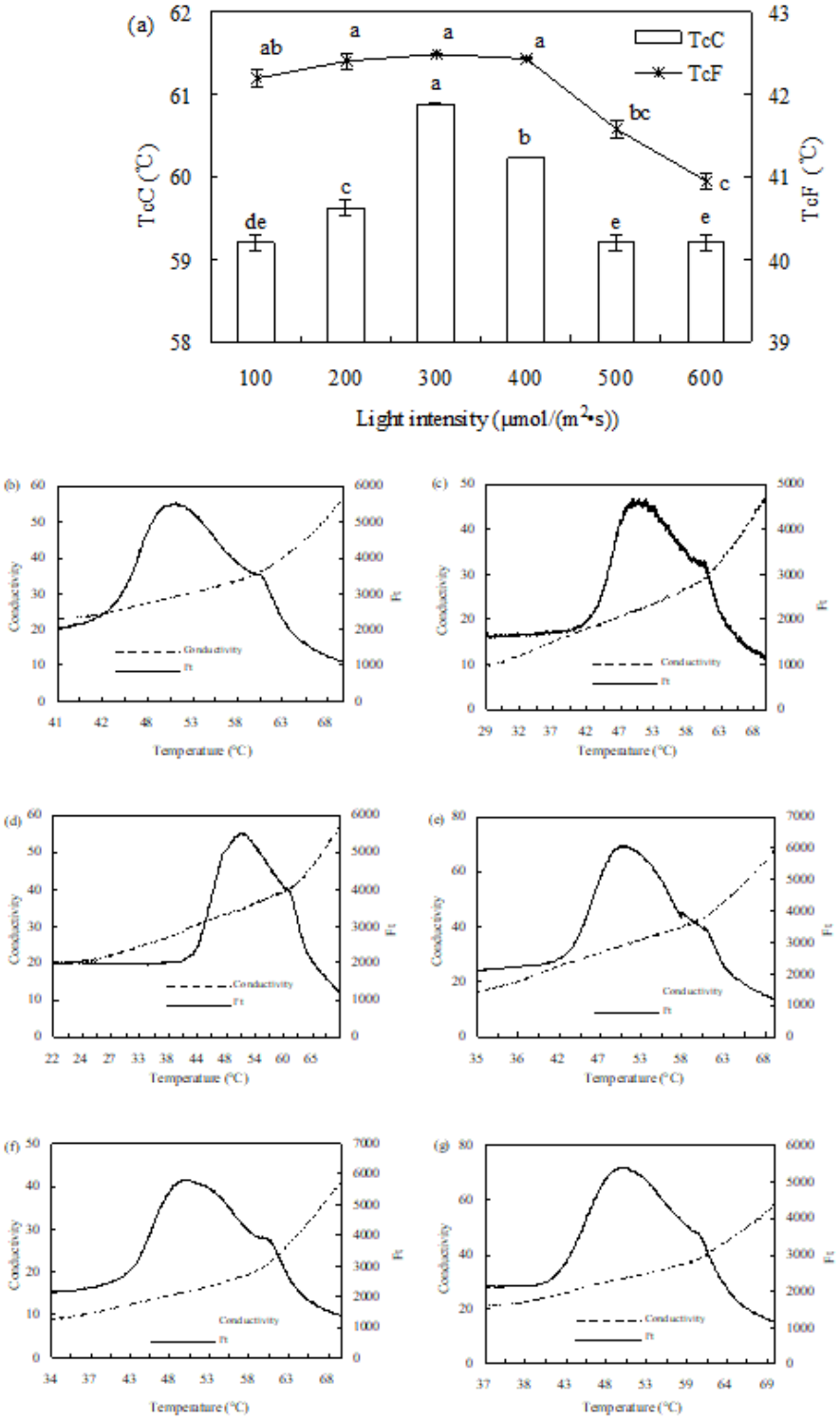

Figure 2

Light intensity effect on perennial ryegrass leaf heat stability. (a): Light intensity effect on TcC and TcF; (b): 100 μmol/(m^2•s) light intensity effect on leaf Conductivity and Ft; (c): 200 μmol/(m^2•s) light intensity effect on leaf Conductivity and Ft; (d): 300 μmol/(m^2•s) light intensity effect on leaf Conductivity and Ft; (e): 400 μmol/(m^2•s) light intensity effect

on leaf Conductivity and Ft; (f): 500 µmol/(m^2•s) light intensity effect on leaf Conductivity and Ft; (g): 600 µmol/(m^2•s) light intensity effect on leaf Conductivity and Ft.

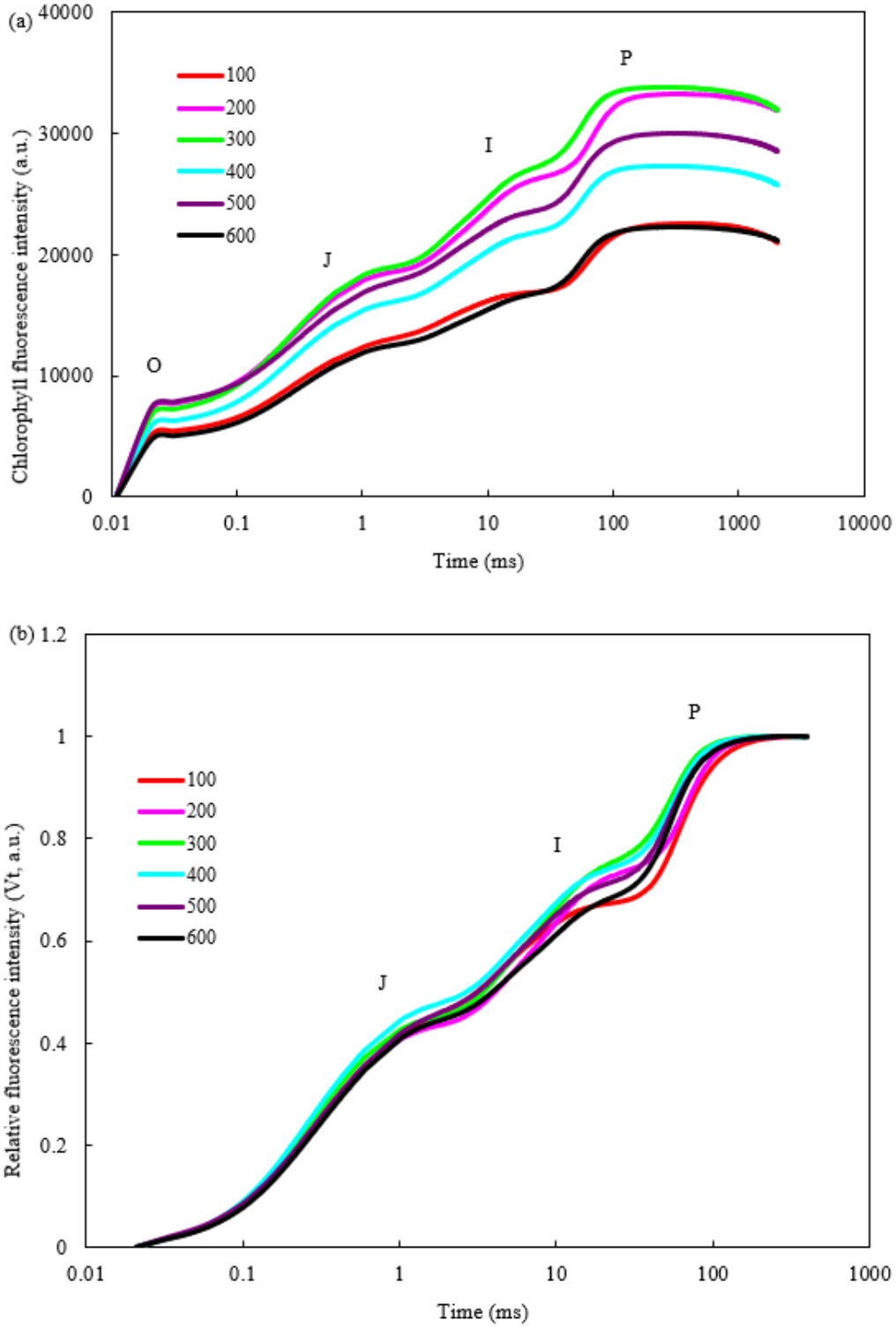

Figure 3

Changes in the shape of the fluorescence transient curves (J-I-P test) measured at 6 different lighting intensities in perennial ryegrass leaves. Each curve represents the

average of 3 independent measurements. (a): the fluorescence transient curves; (b): Relative fluorescence intensity change curves.

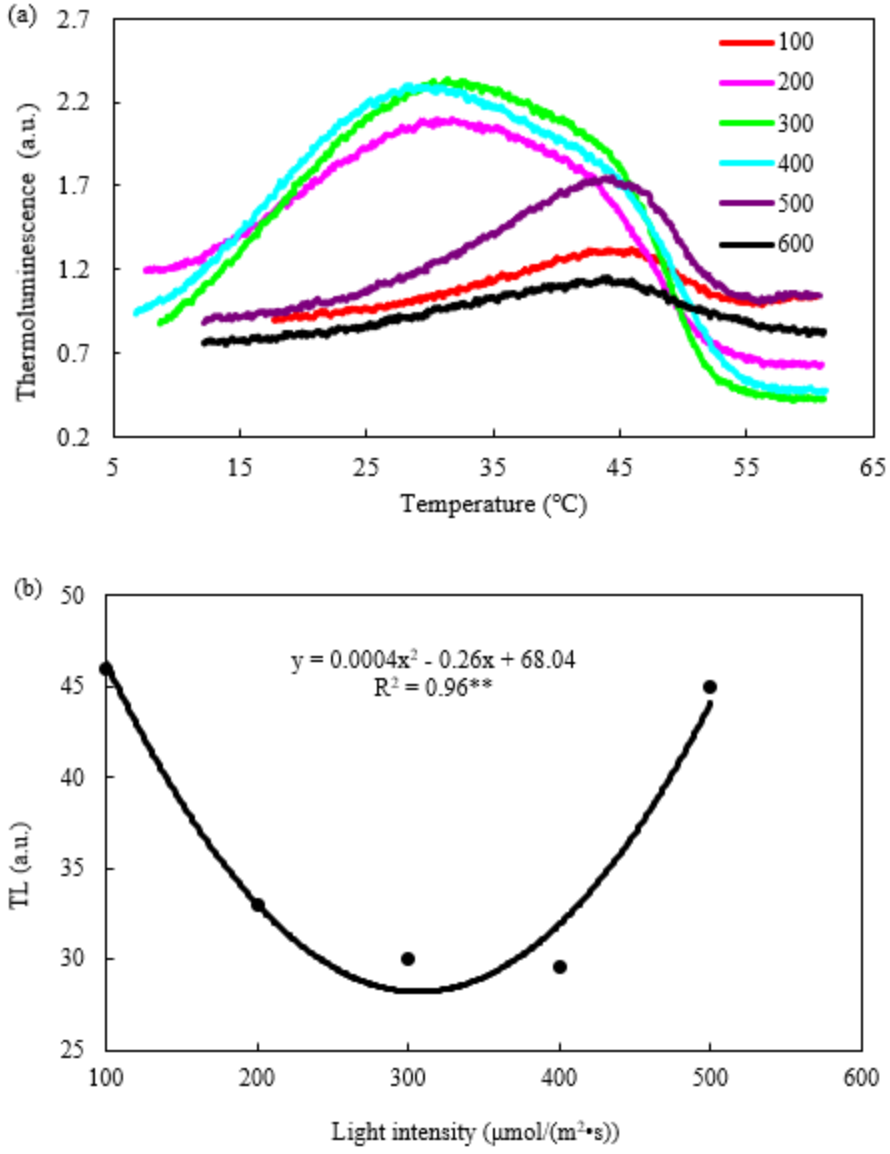

Figure 4

Changes in the leaf photosynthetic thermoluminescence (TL) curves measured at 6 different lighting intensities in perennial ryegrass. (a): Change curves of leaf photosynthetic thermoluminescence under 6 different lighting intensities; (b): Relationship between TL and light intensity.

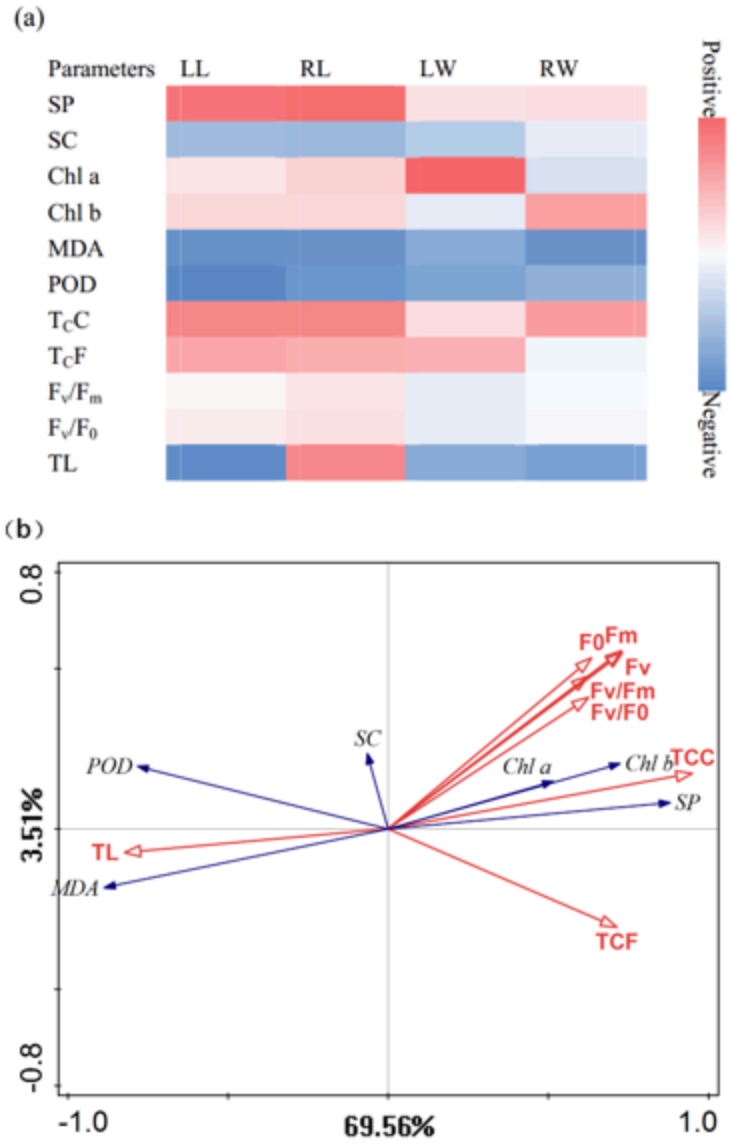

Figure 5

Correlation and redundancy analysis (RDA) among leaf physiological characters, chlorophyll fluorescence parameters and thermoluminescence (TL) temperatures at 6 different lighting time. (a): The correlation among leaf physiological characters, chlorophyll fluorescence parameters and thermoluminescence; (b): The RDA analysis of leaf physiological characters, chlorophyll fluorescence parameters and thermoluminescence.