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ORIGINAL ARTICLE

Characterising the influence of acid rain on the growth and physiological characteristics of *Mirabilis jalapa* Linn. in southern China

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Abstract

Acid rain has progressively become more problematic due to increasing concentrations of atmospheric pollution, particularly in China. *Mirabilis jalapa* L. is an important landscaping ground cover plant with significant resistance to multiple stressors, yet its tolerance to acid stress is unknown. In this study, the effects of acid rain on the growth and numerous physiological indexes of *M. jalapa* at different growth stages such as plant height, leaf growth, chlorophyll content, and chlorophyll fluorescence were investigated under increasingly acidic conditions of pH 5.6 (control), pH 4.0, pH 3.0, and pH 2.0. We found that the plant height, leaf length, and leaf area of *M. jalapa* varied significantly across our four treatments ($P < 0.05$). As the simulated acid rain pH decreased, the plant height, leaf length, and leaf area showed the trend of first increasing before decreasing. In the peak at pH 4.0 treatment, the plant height, leaf length, leaf area, and chlorophyll content were significantly higher than that of the control, pH 3.0 and pH 2.0 ($P < 0.05$). There are significant differences in chlorophyll fluorescence parameters under different treatments ($P < 0.05$). The actual photochemical efficiency (Φ_{PSII}) and apparent electron transfer rate (ETR) of the leaves of *M. jalapa* in the control group, pH 4.0 and 3.0 acid rain stress were significantly higher than that under pH 2.0 stress, while the chemical quenching coefficient (qN) was lower. Chlorophyll fluorescence parameters under control and pH 3.0 treatments were different but not significant ($P > 0.05$), indicating that *M. jalapa* seedlings under pH 4.0–3.0 acid rain treatments had higher photorespiration ability. Whereas *M. jalapa,* under severe stress pH 2.0, increased heat dissipation capacity by absorbing the photorespiration ability. We conclude that acidic conditions of pH of 3.0 were the threshold limit, and acid rain below this value could potentially have a detrimental effect on actual photochemical efficiency. *M. jalapa* had better adaptability under the decreased acidic conditions, rain concentration pH 4.0 to 3.0, which promoted its growth.

Keywords *Mirabilis jalapa* Linn. · Simulated acid rain · Plant growth · Chlorophyll content · Chlorophyll fluorescence

Introduction

Recently, acid rain has dramatically increased as a result of human activities, e.g., rapid economic development, fertilizer application, and fossil fuel combustion (Masamichi et al. 2020; Gimeno et al. 2001). Moreover, this trend is predicted to increase in the near future, particularly in East and South Asia. As a developing country, South China is one of the three major regions among terrestrial ecosystems to receive a significant amount of acid rain (Li et al. 2021). As of 2018, there are 530,000 km^2 susceptible to acid rain in China, and the proportion of acid rain in the 494 cities and counties monitored nationwide is 37.6% (Ministry of Ecology and Environment of the People's Republic of China 2018). The increasing land area affected by acid rain is also

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accelerating, which is one of the critical factors restricting China's agricultural and forestry production and sustainable development (Larssen et al. 2006). At present, there are many studies on the effects of acid rain on plants at home and abroad, mainly focusing on the research of agricultural and forestry crops. For example, under acid rain stress, plant height, chlorophyll content, and the photosynthesis of crops or cash crops at different growth and development stages were significantly impacted (Ilomuanya et al. 2019; Khan and Khan 2010). Few studies investigate landscape plants with ornamental and medicinal value, especially *Mirabilis jalapa* Linn., which exhibits resistance to sulfur dioxide (Xue et al. 2011).

Mirabilis jalapa is native to tropical America and was introduced into China because of its anti-fertility, anticancer, anti-diabetes, and other pharmacological effects. In addition to its ability to purify the environment, such as anti-sulfur dioxide, carbon monoxide, and chlorine (Chen et al. 2008). Researchers have studied the acid tolerance of 30 kinds of herbaceous ornamental plants. With the increase of acid rain concentration, the leaf area of most herbaceous ornamental plants increases, and the tolerance range of different plants to acid rain varies. Under the concentration of pH 1.0, the vast majority of greening plants will rapidly die (Ruuhola et al. 2009; Zhang et al. 2007). Rates of global warming, nitrogen deposition, and acid deposition are accelerating. However, we still don't fully understand the mechanisms and the extent of damage that acid rain can cause to landscape plants, especially regarding the photosynthetic response of plants with acid tolerance (Zheng et al. 2018; Gao et al. 2020). In areas with a high incidence of acid rain, it is essential to select suitable plants for environmental greening and ecological restoration, to understand the response mechanisms of plant growth to acid rain under the background of global climate change, and to reveal the photosynthetic physiological characteristics of plants under environmental stress. These are also critical in formulating scientific and reasonable environmental greening and ecological restoration schemes (Haenel and Tielboerger 2015; Gao et al. 2018).

Mirabilis jalapa has an extensive ecological range and can adapt to acidic soil, but it also exhibits specific invasion characteristics (Xu et al. 2008). The hilly area in Central Sichuan is a high-frequency area where wild *M. jalapa* appears. Although the extreme acidic rain (pH value of annual precipitation is less than 4.0) in Southwest Sichuan and Guizhou has gradually disappeared, the intensity of acid rain in Central China and Central South China, such as Hunan, Guangdong, and Jiangxi, is increasing. *M. jalapa* can resist sulfur dioxide and purify the environment; the effects of acid rain on the photosynthetic physiological characteristics of plant are still not well understood. In this paper, the effects of different concentrations of simulated acid rain on plant height, leaf size, chlorophyll content, and chlorophyll fluorescence parameters of *M. jalapa* seedlings at different growth stages are discussed. We provide a theoretical basis for further elucidating the influence mechanisms of acid rain stress on the growth of acid-tolerant plant *M. jalapa* and provide a reference for the rational use of this species in landscaping.

Materials and methods

Overview of the research area

The research site is located in the experimental base of School of life sciences, China West Normal University, Nanchong, Sichuan (30°49′ N, 106°04′ E), at an altitude of 300 m. The area has a subtropical humid monsoon climate, with an average annual temperature of 15.8–17.8 ℃ and an average annual rainfall of 980–1150 mm (Dong et al. 2013). The concentrations of SO_2 and NOx were provided by the National Air Quality Monitoring Network, precipitation was collected monthly from January 2016 to December 2018, and the background value of acid deposition and pH value of local soil (0–30 cm) were measured (Fig. 1). According to the statistical analysis of the chemical composition of acid rain precipitation in Nanchong from 2016 to 2018 the precipitation pollution in Nanchong is mainly affected by the precursors of SO_4^{2-} and NO_3^-, SO_2 and NOx. Among them, the average concentration ratio of SO_4^{2-} and NO_3^- in the precipitation in Nanchong is 2.2:1(Table 1), indicating that the main anion component in the precipitation in Nanchong is SO_4^{2-}, and precipitation pollution is greatly affected by sulfur oxides. The acid rain in Nanchong is of sulfuric acid type, mainly caused by man-made SO_2 pollution (Luo et al. 2020). The rainfall was mainly light acid rain, and the pH value ranged from 4.67 to 5.67. The pH value was high in winter and spring but low in summer and autumn; the average soil pH value was 5.1 (Fig. 1).

Material and test design

In February 2019, the seedlings were cultivated with the seeds of *M. jalapa*. In the first ten days of March 2019, the seedlings with good and consistent growth were selected to be transplanted into flowerpots with a height of 30 cm and a width of 20 cm. The local red soil (pH 5.1) was taken as the cultivation soil, and three seedlings of *M. jalapa* were transplanted in each basin. Placed in a semi-closed greenhouse for routine management. From May to November 2019, the same volume of simulated acid rain was sprayed every three days. The acid rain configuration method was based on the pH value of acid precipitation in the test site and the proportion commonly used in simulated acid rain

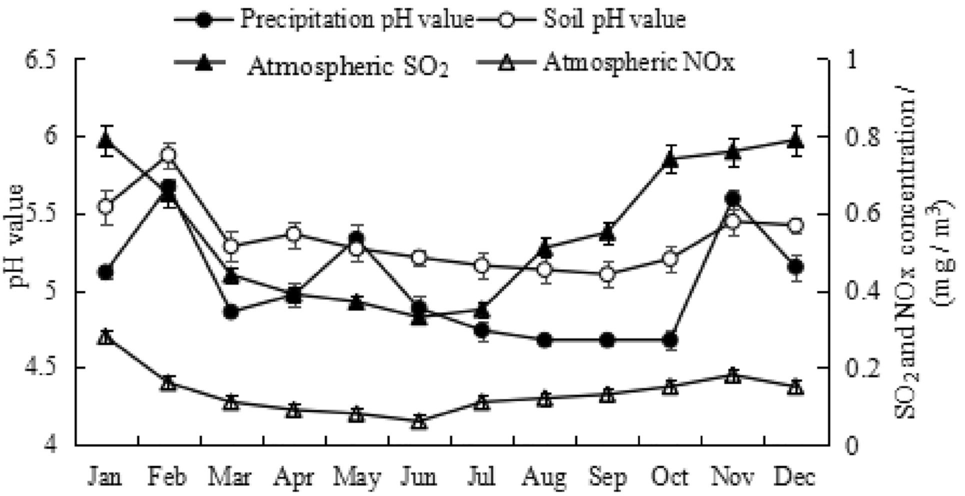

Fig. 1 Atmospheric SO_2, NO_x, precipitation and soil pH in the experimental area from 2016 to 2018

Table 1 The monitoring result of mean chemical composition of precipitation in Nanchong from 2016 to 2018

Year	SO_4^{2-}	NO_3^-	F^-	Cl^-	NH_4^+	Ca^{2+}	Mg^{2+}	Na^+	K^+	H^+
2016	39.23	15.21	3.64	7.54	19.43	31.32	5.47	5.26	3.44	22.25
2017	40.58	17.89	4.67	8.34	20.67	29.57	5.32	6.32	4.68	25.56
2018	32.46	17.43	5.06	7.89	18.79	27.28	5.78	4.67	3.46	24.32

experiments. The mother liquor was configured according to $H_2SO_4:HNO_3 = 8:1$, diluted with distilled water to acid rain solution with a pH value of 5.6, 4.0, 3.0, and 2.0, and pH 5.6 as control. During the experiment, the simulated acid rain was sprayed from the leaves until it dripped into the soil. The total amount of acid rain spray was 1005 mm in terms of multi-year average precipitation × acid water frequency. According to the average monthly precipitation in Nanchong from 2016 to 2018, the monthly spray amount is allocated, divided into 10 uniform sprays, and the total amount of water added is adjusted to the actual monthly precipitation. The treatment and control groups were treated with equal amounts of water to maintain equal soil humidity.

Plant growth and determination of chlorophyll content in leaves

The plant height, leaf size, and chlorophyll content of leaves were measured in May (Spring), August (Summer), and November (Autumn) 2019, respectively. Leaf area was measured by li-3000c portable leaf area meter. The content of chlorophyll photosynthetic pigments was determined by Determination of chlorophyll content using acetone ethanol extraction method (Santos et al. 2020). In May (Spring), August (Summer), and November (Autumn) 2019, the leaves (100 g), which were developed entirely in the middle of the seedlings, were collected and stored in an icebox and returned to the laboratory. The determination of chlorophyll content was carried out by acetone ethanol extraction. 0.2 g of fresh leaves were weighed, cut, and placed into test tubes with 20 ml of extract (anhydrous ethanol: acetone: water = 4.5:4.5:1) before being maintained in darkness for 24 h (Schlemmer et al. 2005; Bayaer et al. 2015). The content of photosynthetic pigments was determined by APL-754N UV visible spectrophotometer produced by Shanghai orpler Instrument Co., Ltd.

Determination of chlorophyll fluorescence parameters in leaves

In May 2019 (Spring), August (Summer), and November (Autumn), the characteristic parameters of chlorophyll fluorescence were measured by a portable modulation chlorophyll fluorescence meter (PAM-2100, Walz, Germany). Five plants were randomly selected for each treatment, and the upper mature and fully expanded leaves were selected for determination, with the average value of three measurements recorded. Before the determination, the leaves to be tested were dark-adapted for 20 min. The fluorescence induced kinetic curve of the leaves and the quantum efficiency of noncyclic electron transfer of PSII (Φ_{PSII}), the maximum photochemical efficiency (F_v/F_m), the potential activity (F_v/F_o), the number of photochemical quenching systems (qP) and the non-photochemical quenching coefficient (qN) were measured. The apparent electron transfer rate $ETR = 0.58 \times \varphi_{PSII} \times PAR \times 0.5$, photochemical quenching coefficient $(qP) = (F'_m - F'_s)/(F'_m - F'_o)$ (Li et al. 2005; Bayaer et al. 2015).

Data analysis

SPSS 20.0 statistical analysis software was used to analyze data. One-way ANOVA was used to compare different acid rain treatments, and the LSD method was used for multiple comparisons. Before data analysis, all data were tested for normality and homogeneity, and Excel 2019 was used to make a drawing.

Results

Effect of simulated acid rain on the growth of *M. jalapa*

The plant height and leaf growth of jasmine under four simulated acid rain treatments were significantly different during different periods of growth season (Fig. 2). With the decrease of pH, the plant height of jasmine seedlings initially increased before subsequently decreasing. The height of plants decreased concomitant with increasing acid rain concentration (3.0) from May to August, but the difference was not significant. The plant height was inhibited with the decreasing pH, indicating that the light and moderate simulated acid rain would not affect the plant height in the short term. Overall, acid rain stress with pH 4.0 significantly promoted the growth of *M. jalapa*. With the decrease in concentration, the growth of *M. jalapa* was inhibited, and the plant height of pH 2.0 simulated acid rain treatment group had little change in the growing season. The leaf length (Fig. 2b), leaf width (Fig. 2c) and leaf area (Fig. 2d) all increased initially before decreasing. Acid rain stress with a pH value of 4.0 significantly promoted the growth of leaf length and leaf area of *M. jalapa* ($P < 0.05$). In contrast, acid rain stress with a pH value of 2.0 significantly reduced the growth of leaf length, width, and leaf area of jasmine in the growing season. The difference between the control and the pH 3.0 simulated acid rain treatment groups was not

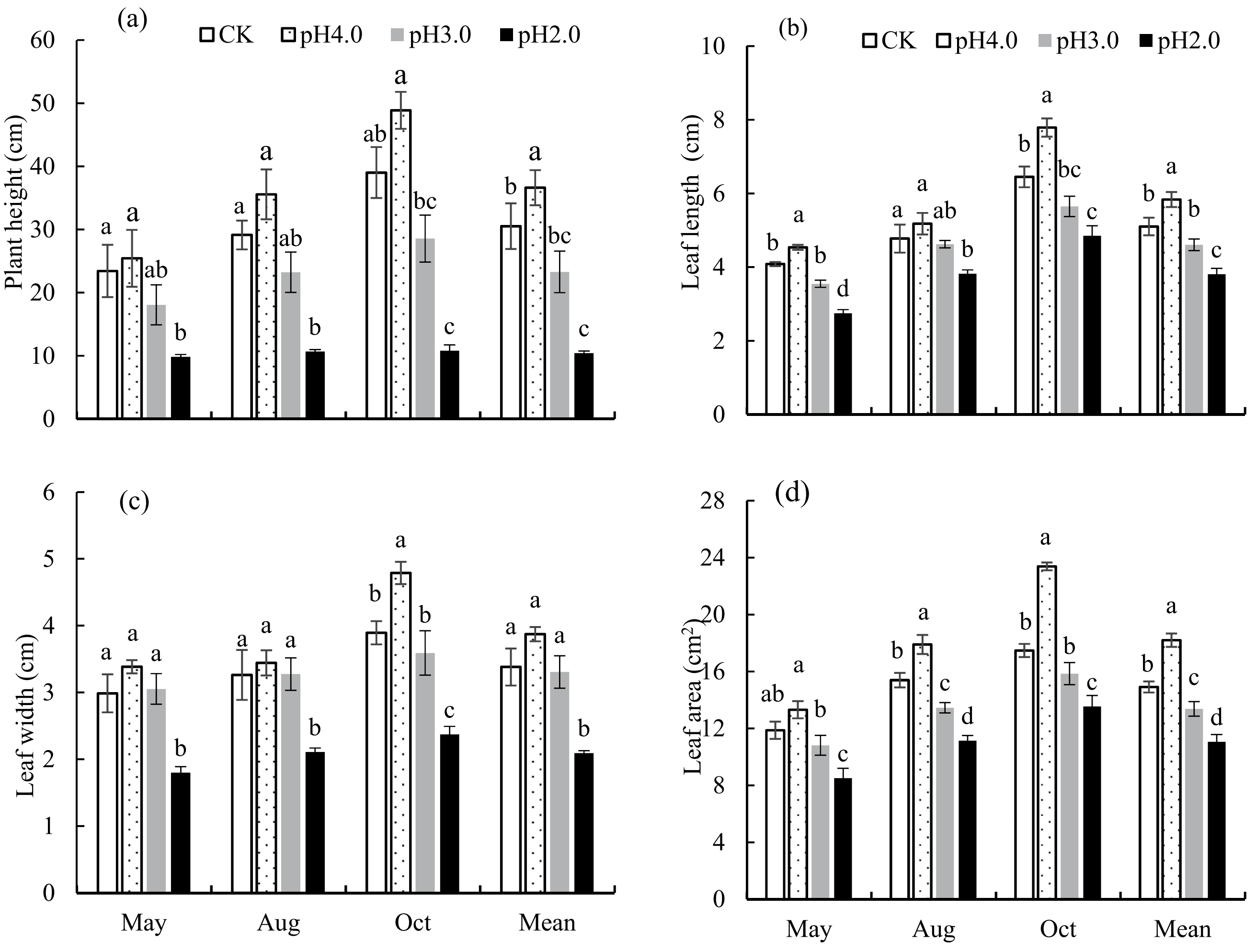

Fig. 2 Effects of plant height (**a**) and the growth of leaves (**b**–**d**) exposed to different simulated acid rain treatments. Each value represents mean ± standard error; different letters indicate significantly different values among our four acid rain treatments (LSD, $P < 0.05$ or $P < 0.01$)

significant ($P > 0.05$). In general, in the pH value 4.0 simulated acid rain treatment group, plant height, and leaf growth increased significantly ($P < 0.05$). As opposed to in the pH 2.0 simulated treatment, which reduced the plant height and the overall growth of leaves of *M. jalapa*, and the difference was significant compared with the control group. Given the change of the direct growth index (plant height, leaf length, leaf width, and leaf area) of *M. jalapa* under different acid rain stress, we speculate that jasmine is an acid resistant plant, and mild acid rain actually promotes its growth, while severe acid rain can damage the plant and inhibit its growth.

Effects of simulated acid rain on chlorophyll content of *M. jalapa* leaves

The chlorophyll *a* (Chl *a*) content of *M. jalapa* leaves varied significantly across different growth stages and different simulated acid rain treatment groups, pH 4.0 > CK and pH 3.0 > pH 2.0 (Table 2). During May to August, there were non-significant ($P > 0.05$) differences in CK and pH 3.0; while there were significant ($P < 0.01$) differences in October, pH 4.0 > CK > pH 3.0 > pH 2.0. Similar patterns were also observed with Chlorophyll *b* (Chl *b*) and Chl contents. In different growth stages, they were pH 4.0 > CK and pH 3.0 > pH 2.0. There was no significant difference between pH 3.0 stress and the control group ($P > 0.05$), but the Chl *b* content of leaves under pH 3.0 stress was higher than that of the control group. This result indicates that pH 3.0 stress significantly influenced Chl b content while the acid rain had no significant effect; only acid rain with high acidity significantly affected Chl b content.

Effects of simulated acid rain on chlorophyll fluorescence parameters of *M. jalapa*

Chlorophyll fluorescence parameters under different simulated acid rain treatments were significantly different ($P < 0.05$), indicating that light energy utilization varied significantly across different acid environments. The F_v/F_m values (0.75–0.85) of seedling's leaves under the control and pH 4.0–3.0 simulated acid rain treatments were not significantly affected. Indicating that the PSII system of *M. jalapa* grown under pH 4.0–3.0 simulated acid rain treatment had typical light energy conversion efficiency (Fig. 3a). However, compared with the control group, F_v/F_m of the simulated acid rain treatment group at pH 2.0 (0.442–0.434) was significantly lower ($P < 0.05$), indicating that the growth of *M. jalapa* under this acid rain concentration was inhibited by light. There were significant differences in the value of Φ_{PSII} under different simulated acid rain treatments ($P < 0.05$, Fig. 3b), and the growth stages were pH 4.0 > CK, and pH 3.0 > pH 2.0, but there was no significant difference between the control and pH 3.0 groups ($P > 0.05$). With the decrease of acid rain concentration, the actual photochemical quantum yield of PSII of *M. jalapa* increased before declining alongside the decrease of simulated acid rain pH. It reached its maximum at pH 4.0, and the minimum was observed at pH 2.0, with significant differences compared with the control ($P < 0.05$), indicating that *M. jalapa* was the most sensitive to simulated acid rain treatment at pH 2.0, whereby it suffered the most damage.

The heat dissipation capacity of *M. jalapa* under different treatments was different in different growth stages (Fig. 3c).

Table 2 Effects of simulated acid rain on chlorophyll content in leaves of *M. jalapa*

Item	pH	May (LSD)	Aug (LSD)	Oct (LSD)	Mean (LSD)
Chla/mg·g^{-1}	CK	0.930 ± 0.034b	1.175 ± 0.022b	0.979 ± 0.025b	1.028 ± 0.033b
	4.0	1.478 ± 0.060a	1.723 ± 0.048a	1.527 ± 0.051a	1.576 ± 0.059a
	3.0	0.685 ± 0.021bc	0.930 ± 0.009bc	0.734 ± 0.012c	0.783 ± 0.021c
	2.0	0.449 ± 0.022c	0.694 ± 0.010c	0.598 ± 0.013d	0.580 ± 0.021d
Chlb/mg·g^{-1}	CK	0.279 ± 0.027b	0.504 ± 0.037b	0.389 ± 0.043b	0.391 ± 0.027b
	4.0	0.475 ± 0.022a	0.700 ± 0.032a	0.585 ± 0.038a	0.587 ± 0.022a
	3.0	0.318 ± 0.008b	0.543 ± 0.017b	0.428 ± 0.024b	0.429 ± 0.008b
	2.0	0.133 ± 0.008c	0.358 ± 0.017c	0.243 ± 0.024c	0.244 ± 0.008c
Total-Chl/mg·g^{-1}	CK	1.209 ± 0.024b	1.679 ± 0.029b	1.368 ± 0.021b	1.418 ± 0.024b
	4.0	1.953 ± 0.020a	2.423 ± 0.036a	2.112 ± 0.077a	2.163 ± 0.080a
	3.0	1.002 ± 0.024b	1.472 ± 0.019b	1.161 ± 0.022b	1.212 ± 0.023b
	2.0	0.582 ± 0.030c	1.052 ± 0.035c	0.841 ± 0.026c	0.825 ± 0.030c
Chla/b	CK	3.422 ± 0.472a	2.350 ± 0.191a	2.551 ± 0.265a	2.667 ± 0.273a
	4.0	3.115 ± 0.058a	2.462 ± 0.033a	2.611 ± 0.040a	2.688 ± 0.041a
	3.0	2.157 ± 0.079b	1.714 ± 0.043b	1.716 ± 0.055b	1.824 ± 0.055b
	2.0	3.390 ± 0.072a	1.940 ± 0.025b	2.464 ± 0.030a	2.375 ± 0.031a

Each value represents mean ± standard error; different letters indicate significantly different values among our four acid rain treatments (LSD, $P < 0.05$ or $P < 0.01$)

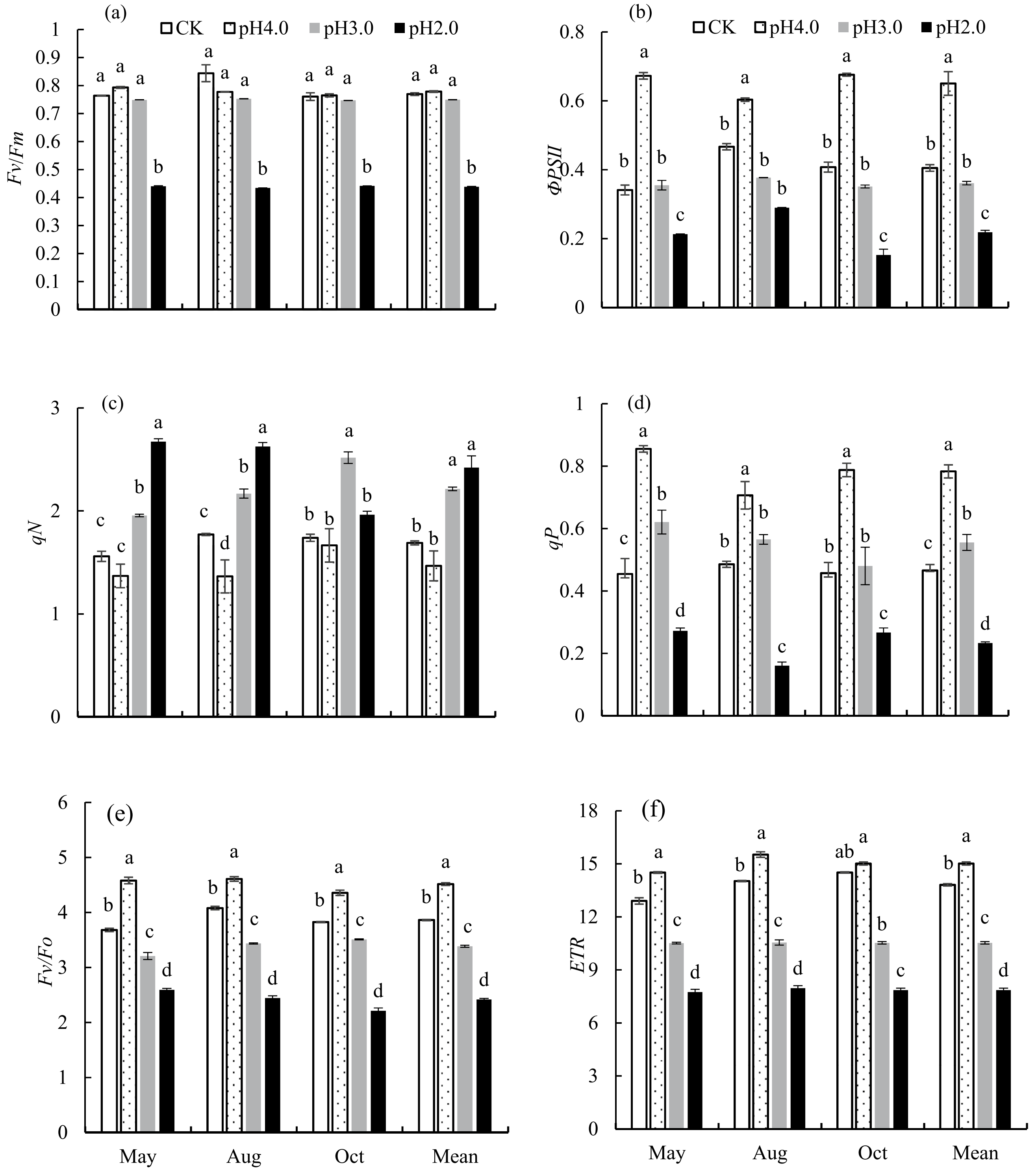

Fig. 3 Effect of simulated acid rain on chlorophyll fluorescence parameters of *M. jalapa*. **a** F_v/F_m: maximal photochemical efficiency of PSII; **b** Φ_{PSII}: actual photochemical efficiency; **c** *qN*: non-photochemical quenching coefficient; **d** *qP*: photochemical quenching coefficient; **e** F_v/F_o: potential activity of PSII; **f** *ETR*: apparent electron transfer rate. Each value represents mean ± standard error; different letters indicate significantly different values among our four acid rain treatments (LSD, $P < 0.05$ or $P < 0.01$)

The QN value of pH 2.0 was higher from May to August than the average value, implying a strong heat dissipation ability. Therefore, the proportion of light energy absorbed by the PSII antenna pigments for heat dissipation was significantly higher under pH 2.0 than that under other treatments, while the proportion for photosynthesis was lower. This further indicates that the proportion of light energy absorbed by PSII antenna pigment for heat dissipation was significantly higher under pH 2.0 than that under other treatments. The growth status of *M. jalapa* under the treatment of 3.0–2.0 was less than that of the control and pH 4.0. *qP* reflects the proportion of light energy absorbed by antenna pigment for photochemical electron transfer, the openness of PSII, and the reduction of primary electron acceptor (Q_A). The *qP* value of pH 4.0 was significantly higher than that of other treatments at all growth stages ($P < 0.05$), implying that moderate acid rain could increase the light energy utilization effect of *M. jalapa*. The F_v/F_o values under different acid rain treatments were significantly different ($P < 0.01$), and they were pH 4.0 > CK > pH 3.0 > pH 2.0 at different growth stages, indicating that the light energy captured by *M. jalapa* leaves under pH 4.0 acid rain concentration could be more effectively converted into the energy. The higher the ETR value, the stronger the ability of the plant to transfer effective quantum to photoreaction. The ETR values under different acid rain treatments were significantly different ($P < 0.05$). From May to August, the average values were pH 4.0 > CK > pH 3.0 > pH 2.0. In October, there were nonsignificant differences between the control and pH 4.0, while both were significantly higher than pH 3.0 and pH 2.0.

Discussion

Plant height and leaf morphology can reflect the adaptability of plants to the environment under different environmental stresses, and the effect of acid rain on plants is ultimately reflected in their morphological structures (Guenni et al. 2018; Liang et al. 2008). In this study, simulated acid rain at pH 4.0 can promote the growth of plant height and leaves, and simulated acid rain at pH 2.0 can inhibit the growth of *M. jalapa*. Meanwhile, *M. jalapa* can tolerate simulated acid rain at pH 3.0 and still grow normally under this condition (Pignattelli et al. 2021). Under simulated mild acid rain conditions, acid rain can promote the plant height of some plants (Chen et al. 2019a, b). The higher plant height and larger leaves of *M. jalapa* under the simulated acid rain condition of pH 4.0 indicate that *M. jalapa* has increased the acquisition and utilization of resources in both height and breadth. Still, too low pH inhibits the growth of *M. jalapa*, which is consistent with the research results of *Magnolia grandiflora, Cinnamomum camphora,* and *Osmanthus fragrans* under the simulated acid rain condition (Fu et al. 2006). Under the stress of an acid rain environment, especially when the acid rain directly contacts the leaves of plants, plants will reduce the leaching damage of acid rain by reducing the contact surface. This strategy also increases the tolerance of *M. jalapa* to acid rain to a certain extent.

Chlorophyll is the main factor in maintaining plant photosynthesis. The change of its content and proportion is an important indicator for plants to adapt to changing environmental factors and the adaptive response of plants to environmental stress (Hao et al. 2014). Under moderate acid rain (pH 3.0), the relative chlorophyll content of *M. jalapa* plants increased with time, which may be related to the self-protection of plants by synthesizing chlorophyll and improving photosynthetic capacity. Under the simulated acid rain condition of pH 4.0, *M. jalapa* seedlings grew well. Their chlorophyll content was relatively high, with chlorophyll a, chlorophyll *b*, and total chlorophyll contents greater than in the controls. The effect of pH 3.0 acid rain on the chlorophyll content of *M. jalapa* seedlings was not noticeable; only the acid rain treatment of pH 2.0 decreased significantly. This is different from the results of Tong and Qiu, who identified that acid rain stress inhibited the formation of chloroplast and the synthesis rate of chlorophyll, resulting in a significant decrease in chlorophyll content (Tong and Liang 2005; Qiu and Liu 2002). This may be because *M. jalapa* can tolerate acid rain, as moderate SO_4^{2-} and NO_3^- in simulated acid rain at pH 4.0 can increase the nitrogen and sulfur elements in soil and promote the growth of *M. jalapa.* Therefore, the leaves of *M. jalapa* only showed functional damage under high acid rain stress but had a certain tolerance to mild and moderate acid rain stress. Overall, the chlorophyll content of *M. jalapa* seedlings increased first and then decreased with the decrease of simulated acid rain pH, which indicated that the simulated acid rain value could significantly impact the chlorophyll content of *M. jalapa* seedlings and promote the chlorophyll synthesis of *M. jalapa*. The short-term severe acid rain has little effect on the chlorophyll content of *M. jalapa*. When the acid rain concentration and stress time reached a certain threshold, the chlorophyll content was affected, which further indicates that *M. jalapa* has strong acid tolerance.

Chlorophyll fluorescence technology is a fast, sensitive, and non-invasive technology, which is a proxy for photosynthesis. The effect of any environmental stress on plant photosynthesis can be determined by chlorophyll fluorescence, and its change degree can be used to identify the ability of plants to resist stress (Mao et al. 2020; Chen et al. 2019a, b). There is a positive correlation between chlorophyll fluorescence parameters and the degree of plant stress (Hidri et al. 2016). In this study, the F_v/F_m value of acid rain at pH 3.0 was lower than 0.75, which indicated that the growth of *M. jalapa* seedlings was inhibited by light. Photosynthetic quantum yield is used to measure the quantum yield of photosynthetic electron transfer in plants, which can be used as the relative index of photosynthetic electron transfer rate in plant leaves. In this study, the actual photosynthetic efficiency, potential photochemical activity, and photochemical quenching coefficient of different acid rain concentrations exhibited significant differences compared with the control group, indicating that *M. jalapa* seedlings were sensitive to different acid rain concentrations. This is consistent with other researchers' research on chlorophyll fluorescence characteristics of the same plant under various environmental stresses (Thwe et al. 2020; Wang and Nii 2015). Among many fluorescence parameters, high F_v/F_m, $F_v/F_{o,}$ and Φ_{PSII} values have been considered as an important basis for high photosynthetic efficiency of leaves, and many studies have pointed out that F_v/F_m, $F_v/F_{o,}$ and Φ_{PSII} have good consistency (Chen et al. 2019a, b). In our study, F_v/F_m, $F_v/F_{o,}$ and Φ_{PSII} were significantly increased by acid rain at pH 4.0. The seedlings of *M. jalapa* could still grow normally at pH 3.0, and there was no significant difference between the various treatments. pH 2.0 treatment decreased F_v/F_m, $F_v/F_{o,}$ and Φ_{PSII} of *M. jalapa*, which indicated that the PSII reaction center of chloroplast was damaged after *M. jalapa* exceeded the tolerance of acid rain stress; the decrease of Φ_{PSII} also showed that photosynthetic electron transfer was blocked. The non-chemical quenching coefficient was higher at pH 2.0, potentially revealing that the light energy absorbed by *M. jalapa* seedlings at this concentration was mainly used for heat dissipation; thus, the actual photochemical efficiency was relatively low.

There are certain thresholds for the influence of acid rain on plant growth and development. To determine the threshold of garden plants under adversity stress, in addition to considering their growth morphological indicators from the appearance, certain physiological and biochemical indicators must also be determined (Bruno et al. 2006; Guenni et al. 2018; Iummato et al. 2019). The results of this test showed that the pH 2.0 acid rain treatment had significant differences in the photosynthetic physiological indicators of *M. jalapa*. Therefore, it was preliminarily determined that the damage threshold of simulated acid rain to *M. jalapa* is less than pH 2.0; the impact threshold on the physiological activities of *M. jalapa* is roughly at pH 2. 0–3. 0.

Conclusions

Collectively, our results demonstrate that the plant height and leaf growth of *M. jalapa* under acid rain treatment were significantly affected, and *M. jalapa* grew better under slight acid treatment than in the acid-free environment. The acid rain treatment of pH 4.0 was beneficial to the growth of *M. jalapa* seedlings, which further suggests that *M. jalapa* can grow in slightly acidic environments and can even tolerate the moderate acid rain at pH 3.0, as it did not affect the expected growth. Although with the increase of acid rain acidity, inhibition of *M. jalapa* became apparent. *M. jalapa* exhibited the ability to self-repair ability after being damaged by acid rain. Compared with the apparent symptoms, the physiological and biochemical characteristics of plants are more sensitive to acid rain. The visible damage threshold of simulated acid rain on *M. jalapa* was less than pH 2.0, and the threshold for its impact on the physiological activities of *M. jalapa* was roughly at pH 2.0 to pH 3.0. *M. jalapa* has a strong tolerance to acid rain and can be used as one of the species for landscaping and vegetation construction in areas with severe acid rain disasters.

Author contribution statement Lan-ying Chen contributed to the study conception and design. Data collection and experiments were performed by Lin Wang, Hao-yu Wang and Xun Zhu. Hao-yu Wang and Lin Wang analyzed the data. The first draft of the manuscript was written by Lan-ying Chen and Lin Wang, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability statement The data used to support the findings of this study are available from the corresponding author upon request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest. This article does not contain any studies with human participants or animals performed by any of the authors. Informed consent was obtained from all individual participants included in the study.

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