RESPONSE OF THE PS II FUNCTION OF MORUS ALBA VAR. ‘QIUYU’ SEEDLING LEAVES TO DIFFERENT NITROGEN FORMS

XU, N.1,2 – YU, S. P.1,2* – DING, J. N.1,2 – SHI, C. Q.1,2

1Harbin University, Harbin 150086, China
2Key Laboratory of Heilongjiang Province for Cold-Regions Wetlands Ecology and Environment Research, Harbin University, Harbin 150086, China

*Corresponding author
e-mail: wetlands1972@126.com; xunan0451@126.com

(Received 26th Aug 2021; accepted 3rd Dec 2021)

Abstract. In order to gain insights into the effect of different nitrogen forms on the photosynthetic ability of Morus alba, we studied chlorophyll fluorescence characteristics of one-year-old M. alba leaves treated with nitrate-nitrogen (NO$_3^-$-N), ammonium-nitrogen (NH$_4^+$-N) and ammonium nitrate (NH$_4$NO$_3$). We found that the PSII photochemical activity, electron transport rate and light energy usage of the M. alba leaves were significantly lower in plants treated with NH$_4^+$-N compared to those treated with NO$_3^-$-N and NH$_4$NO$_3$. We did not observe a significant difference in photosynthetic parameters between the NO$_3^-$-N and NH$_4$NO$_3$ treatments. There was an increase in the relative variable fluorescence values at the J step ($V_J$) and I step ($V_I$) of M. alba leaves under the NH$_4^+$-N treatment compared to the NO$_3^-$-N and NH$_4$NO$_3$ treatments. In addition, the values of $V_E$ and $V_t$ in M. alba leaves in plants treated with NH$_4^+$-N were significantly lower than the NO$_3^-$-N and NH$_4$NO$_3$ treatments, suggesting that the inhibition of the oxygen-evolving complex (OEC) activity and the declined stability of the thylakoid membrane structure in M. alba leaves contributed to the decline of the photochemical activity in the PSII reaction center under the treatment of NH$_4^+$-N.

Keywords: Morus alba, Chlorophyll fluorescence, nitrogen, photosynthetic, OJIP curves

Introduction

Nitrogen is one of the most important elements for plants. Over half of the nitrogen in plants mainly exists within chloroplasts in the form of enzymes, participating in the photosynthetic metabolic processes (Shangguan et al., 2000) and playing an important role in their growth and development (Wang and Baerenklau, 2014). Except for a small amount of amino acids absorbed by plants, nitrogen is mainly absorbed by the roots in the form of nitrate-nitrogen (NO$_3^-$-N), ammonium-nitrogen (NH$_4^+$-N) and, organic nitrogen (Chapin et al., 1993; Kuelland, 1994). NO$_3^-$-N or NH$_4^+$-N constitutes the major form of absorption (Lin and Lin, 2011). Different plants have unique preferences for the type of nitrogen that the roots absorb. For example, Picea glauca (Kim et al., 2002), Pinus sylvestris (Nordin et al., 2001) and Oryza sativa L. (Matsudo et al., 2009) prefer NH$_4^+$-N, while excessive NH$_4^+$-N can be toxic to the NO$_3^-$-N-preferring plants like Haematococcus pluvialis (Choi et al., 2003) and Neochloris oleoabundans (Li et al., 2008; Pruvost et al., 2009). A relatively high concentration of NO$_3^-$-N can significantly improve the stress resistance of Indian mustard (Nathawat et al., 2007) and Spirulina platensis (Danesi et al., 2002), while the application of NH$_4^+$-N was proven to be more beneficial for Hordeum vulgare L. under salt stress (Ali et al., 2001). Many researches have also been conducted studying the absorption volume, absorption rate, and absorption proportion of NH$_4^+$-N and NO$_3^-$-N in crops such as rice, wheat and...
vegetables such as cabbage, lettuce, and spinach (Ambus et al., 2011; Sutton et al., 2012; Gruffman et al., 2012).

*Morus alba* L. is the most widely cultivated and utilized plant in China. *M. alba* can be classified depending on its applications as *M. alba* for silkworm, consumption, fruit, feed, or virescence and so on (Wang et al., 2004; Liu et al., 2019). *M. alba* leaves are highly nutritious, with protein content similar to alfalfa, which is 80%~100% higher than that of forage grass of the grass family, and 40%~50% higher than that of legume forage (Wang et al., 2004; Liu et al., 2019). *M. alba* leaves are rich in amino acids with appropriate proportions, especially rich in glutamic acid, making the *M. alba* leaves an excellent source of protein, and feed combined with *M. alba* leaves can have an enhanced nutritional value (Xu et al., 2012; Liu et al., 2019). With the development of the “South-north” relocation policy which is aimed to encourage planting *M. alba* trees in the Northern part of China, *M. alba* is being cultivated at an increasing rate. *M. alba* trees are resistant to salinity and drought (Hu et al., 2007; Zhang et al., 2012; Pang et al., 2014), therefore the cultivation acreage of *M. alba* in the saline-alkali soil area of the stock breeding grassland region of Song Nen Plain is relatively large, to help rehabilitate the degraded grassland and increase the forage capacity. However, the cultivation of *M. alba* in the saline-alkali regions of Northwestern Heilongjiang Province has resulted in slow growth before July, likely caused by the low temperature and less rainfall in the spring. In order to speed up the growth of *M. alba* at the early stages, a previous study has found that increasing nitrogen fertilization could promote the growth of *M. alba* (Zhang et al., 2012; Pang et al., 2014) and the appropriate amount of nitrogen application was determined as well.

The strong stress resistance ability of *M. alba* makes it an excellent tree species for vegetation restoration in degraded ecosystems (Sun et al., 2003; Chen et al., 2006; Liu et al., 2019). However, the lack of nitrogen in the soil of these degraded ecosystems limits plant growth, affecting vegetation recovery (Britto et al., 2001; Jan et al., 2013; Guo et al., 2017; Mu et al., 2021). Careful application of nitrogen fertilizer is one of the important measures that can be adopted to speed up the recovery of degraded ecosystems. In our previous study, we found that *M. alba* preferred NO$_3^-$-N. Application of NO$_3^-$-N to *M. alba* increased photosynthetic ability and electron transport rate of the leaves compared to plants that were treated with NH$_4^+$-N (Nathawat et al., 2007). In addition to increased photosynthesis, the salt tolerance of *M. alba* also improved with the application of NO$_3^-$-N (Zhang et al., 2013). However, it remains unclear what causes the high electron transport rate and photosynthetic capacity of *M. alba* under the treatment of NO$_3^-$-N. In this study, chlorophyll fluorescence technology and fast chlorophyll fluorescence kinetics (OJIP) method were used to study the physiological responses of the leaves of *M. alba* seedlings, such as PS II photochemical reactivity, oxygen-evolving complex (OEC) function at the electron donor side, electron transport ability at the electron receptor side, electron storage capacity, thylakoid membrane structure state and light allocation parameters under different nitrogen forms; the reasons for the higher photosynthetic capacities under NO$_3^-$-N treatment compared to NH$_4^+$-N treatment. In order to provide theoretical basis for the rational allocation of tree species in the process of vegetation restoration in the degraded ecological nitrogen deficient area, and provide some basic data and provide some basic data for rational fertilization for *M. alba*.
Materials and methods

Materials

Seeds of Mulberry ‘Qiuyu’ were received from the Heilongjiang Academy of Agricultural Sciences, China. Uniform mulberry seeds with orange color were selected for surface disinfection with 3.0% NaCl solution for 20 min, then washed with sterile water, soaked in sterilized saturated CaSO_4 solution for 6 h, and placed in an incubator at 37°C to accelerate germination. After blanking, the seeds were sown to the culture medium for seedling growth. The medium was fully mixed with fully mixed peatsoil and vermiculite in a ratio of 1:1(V/V). The medium was high-temperature sterilized, and the temperature was 25/23℃ (light/dark), the light intensity was 400 μmol·m^{-2}·s^{-1}, the photoperiod was 12/12 h(light/dark). Cultured in an artificial climate box with relative humidity of about 75%, and managed the seedling stage for about 25 days. When the main radicle of seed germination grew to about 3 cm, seedlings with relatively consistent growth were selected to pull out from the culture substrate, carefully washed the culture substrate on the root surface, and then moved into the culture substrate (length 50 cm; width 40 cm; high 30 cm). The culture medium was Hogland nutrient solution, and the pH value of the medium was 6.0± 0.1. In order to prevent the roots from seeing light, the hydroponic box was wrapped with black light-proof paper, and the electric air pump was used for continuous ventilation. After one week of culture, the seedlings germinated white new roots and began to be treated with nitrogen fertilizer. The molar ratios of (NH_4^+-N) (NO_3^-N) in each treatment were 100:0, 50:50, 0:100, respectively. The concentration of other nutrient elements is completely the same, and the solution formula of each treatment is shown in Table 1. The culture medium was replaced every 3 days. The two upper fully expanded attached leaves of six to eight weeks old plants were used for experiments.

### Table 1. Nutrition composition of the hydroponics solution with different percentage of ammonium and nitrate nitrogen

<table>
<thead>
<tr>
<th>Nutrition Composition</th>
<th>NH_4^+:NO_3^-</th>
<th>100:0</th>
<th>50:50</th>
<th>0:100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca(NO_3)_2 (mmol·L^{-1})</td>
<td>1.50</td>
<td>0.50</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>KNO_3 (mmol·L^{-1})</td>
<td>2.00</td>
<td>1.50</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>(NH_4)_2SO_4 (mmol·L^{-1})</td>
<td>0.00</td>
<td>1.25</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>K_2SO_4 (mmol·L^{-1})</td>
<td>0.00</td>
<td>0.25</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>CaSO_4 (mmol·L^{-1})</td>
<td>0.00</td>
<td>0.50</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>CaCl_2 (mmol·L^{-1})</td>
<td>0.00</td>
<td>0.50</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>K_2HPO_4 (mmol·L^{-1})</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>MgSO_4 (mmol·L^{-1})</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>NaCl (mmol·L^{-1})</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td></td>
</tr>
</tbody>
</table>

Experimental design

The experiment was conducted using a simple randomized block design. There were three treatments of the experiment, with different percentage of ammonium and nitrate nitrogen (NO_3^-N : NH_4^+-N) which were 100:0, 50:0 and 0:100 (Table 1). There were 3 seedlings in each treatment and 3 replicates in each treatment. The growth parameters and
photosynthetic parameters were measured after the seedlings were cultured in different nitrogen nutrient solution for 2 weeks.

**Growth parameters determination**

Select the processing relative consistent growth in mulberry branch contact with the ground diameter, the record for the ground diameter, each treatment for the plant, respectively will be filming for the root and aboveground 105°C for 30 min, 60°C after drying to constant weight according to its weight, or get the underground biomass and biomass on the ground, and calculate the total biomass (the sum of underground biomass and the ground biomass), root-shoot ratio = underground biomass/biomass on the ground.

**Measurement of chlorophyll fluorescence**

PSII Chl fluorescence measurements were done using an FMS-2 portable pulse modulated fluorometer (Hansatch, UK). The maximum PSII quantum yield \( \left( \frac{F_o}{F_m} \right) \) was determined in dark adapted (15 min) samples. After a short log phase, the fluorescence transient was induced by continuous actinic white light (1200 μmol m\(^{-2}\) s\(^{-1}\)) for 2 h, provided by Fluorimeter light source. Maximum quantum yield of PSII \( \left( \frac{F_o}{F_m} \right) \), photochemical quenching coefficient \( \left( q_P \right) \), and the actual PSII efficiency under irradiance \( \left( \Phi_{PSII} \right) \) were calculated according to Genty et al. (1989), Chlorophyll a fluorescence transient was measured with a Handy-PEA fluorometer (Hansatch, UK). Having been dark adapted for 1 h before heat treatment, all the leaves were immediately exposed to a saturating light pulse (3000 μmol·m\(^{-2}\)·s\(^{-1}\) PFD) for 2 s after heat treatment in the dark at different times. Each transient obtained from the dark-adapted samples was analyzed according to the JIP-test (Strasser et al., 1995) by utilizing the following original data: (1) the fluorescence intensity at 20 ms \( (F_o, \text{when all RCs of PSII are open}) \); (2) the maximum fluorescence intensity \( (F_m, \text{when all RCs of PSII are closed}) \) and (3) the fluorescence intensities at 300 ms (K-step), 2 ms (J-step) and 30 ms (I-step). The maximum quantum yield of PSII photochemistry \( \left( \frac{F_o}{F_m} \right) \) was calculated as: \( \frac{F_o}{F_m} = \frac{F_m - F_o}{F_m} \), in this study, \( F_m = F_P \). The relative variable fluorescence intensity at J-step \( (V_J) \) and I-step \( (V_I) \) were calculated as: \( V_J = \frac{F_J - F_o}{F_m - F_o} \) and \( V_I = \frac{F_I - F_o}{F_m - F_o} \). \( V_K \) and \( V_L \) were the relative variable fluorescence on the \( V_{0.1J} \) and \( V_{0.1K} \) point at 0.3 and 0.15 ms.

According to the JIP-test (Strasser et al., 1995; Zhang et al., 2018a) could obtain such as that maximum quantum yield of PSII photochemistry \( \left( \frac{F_v}{F_m} \right) \), Performance index on absorption basis \( \left( \Phi_{ABS} \right) \), Probability that a trapped exciton moves an electron into the electron transport chain beyond \( Q \alpha^\ast \) (at \( t=0 \)) \( \left( \Phi_\Psi \right) \), Quantum yield for electron transport (at \( t=0 \)) \( \left( \Phi_D \right) \), quantum yield of absorption flux to dissipated energy \( \left( \Phi \right) \), Absorption flux per RC \( \left( \frac{F_v}{F_m} \right) \), Trapped energy flux per RC (at \( t=0 \)) \( \left( \frac{ET_o}{RC} \right) \), Electron transport flux per RC (at \( t=0 \)) \( \left( \frac{ET_o}{RC} \right) \) and Dissipated energy flux per RC (at \( t=0 \)) \( \left( \frac{DI_o}{RC} \right) \).

**Statistical analysis**

Excel and SPSS software (Version. 22) were used to conduct statistical analyses on the measured data. The data in the figure was denoted as mean ± standard deviation (SD). One-way ANOVA and least significant difference (LSD) were used to compare the differences among different data groups (n=3).
Results and analysis

The effect of different nitrogen forms on chlorophyll fluorescence parameters in the leaves of mulberry

When NH$^{4+}$-N:NO$^{3-}$-N is 50:50, the above ground biomass and underground biomass of mulberry seedlings reach the highest respectively (2.85 g/ plant and 0.993 g/ plant), and the total biomass from high to low is 50:50, 100:0, 0:100, the difference is very significant (Table 2) ($P<0.05$). The root-shoot ratio of the seedlings was the largest when NH$^{4+}$-N:NO$^{3-}$-N was 100:0, but the difference was not significant when it was 0:100, and the difference was the smallest when it was 50:50, which was 27.3% and 27.2% lower than the former two, respectively, and the difference was significant ($P<0.05$). The ground diameter is the largest when NH$^{4+}$-N:NO$^{3-}$-N is 50:50, which is about 1.5 times of that of 100:0 and 0:100, and the difference is extremely significant.

Table 2. Biomass on leaves of mulberry seedlings to different nitrogen forms

<table>
<thead>
<tr>
<th>NH$^{4+}$-N: NO$^{3-}$-N</th>
<th>Above ground biomass (g)</th>
<th>Underground biomass (g)</th>
<th>Total biomass (g)</th>
<th>Root-shoot ratio (%)</th>
<th>Ground diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100:0</td>
<td>1.21±0.02b</td>
<td>0.308±0.04b</td>
<td>1.519±3.11b</td>
<td>3.98±0.51a</td>
<td>0.31±0.14b</td>
</tr>
<tr>
<td>50:50</td>
<td>2.85±0.06a</td>
<td>0.993±0.10a</td>
<td>3.840±3.90a</td>
<td>2.89±0.37b</td>
<td>0.54±0.15a</td>
</tr>
<tr>
<td>0:100</td>
<td>1.21±0.06b</td>
<td>0.354±0.03bc</td>
<td>1.563±3.66b</td>
<td>3.97±0.19a</td>
<td>0.32±0.15b</td>
</tr>
</tbody>
</table>

The effect of different nitrogen forms on $F_v/F_m$, $\Phi_{PSII}$, $q_p$ and NPQ in the leaves of mulberry

To characterize the effect of NO$_3^-$N, NH$_4^+$-N, NH$_4$NO$_3$ treatment on mulberry leaf photosynthesis parameters, we measured the values of $F_v/F_m$, $\Phi_{PSII}$ and $q_p$ of the M. alba leaves under various treatments. We observed a significant decrease in $F_v/F_m$, $\Phi_{PSII}$ and $q_p$ in plants treated with NH$_4^+$-N compared to NO$_3^-$N and NH$_4$NO$_3$ (Fig. 1). Specifically, we observed a decrease of 9.13% ($P<0.01$), 55.53% ($P<0.01$) and 26.27% ($P<0.01$) for $F_v/F_m$, $\Phi_{PSII}$ and $q_p$, respectively, when compared to NO$_3^-$N, and 10.65% ($P<0.01$), 55.36% ($P<0.01$) and 38.87% ($P<0.01$) when compared to the NH$_4$NO$_3$ treatment respectively. All differences were highly significant. Under NH$_4^+$-N treatment, the NPQ value of mulberry leaves was significantly higher than those treated with NO$_3^-$N and NH$_4$NO$_3$. The differences of the chlorophyll fluorescence parameters of mulberry leaves under the treatments of NO$_3^-$N and NH$_4$NO$_3$ were insignificant.

Responses of $\Phi_{PSII}$ and ETR of mulberry seedling leaves to illumination intensity under the treatment of different nitrogen forms

We next tested the values of $\Phi_{PSII}$ and ETR of mulberry seedling leaves treated by different nitrogen forms under different illumination intensity conditions. In general, we observed that increasing the illumination intensity resulted in a decrease in $\Phi_{PSII}$ of mulberry seedling leaves (Fig. 2). ETR values first increased and then declined upon increased illumination, suggesting that there was light saturation. However, we observed significant differences between the different nitrogen treatments. Plants treated with NO$_3^-$N and NH$_4$NO$_3$ did not show difference in $\Phi_{PSII}$ and ETR at different illumination intensities. However, in plants treated with NH$_4^+$-N, the $\Phi_{PSII}$ was significantly lower at different illumination intensities ($P<0.01$). There was no difference in ETR of plants.
illuminated with 100 and 200 μmol·m⁻²·s⁻¹, but when the illumination intensity exceeded 200 μmol·m⁻²·s⁻¹, the ETR under NH₄⁺-N treatment was significantly lower than those under the treatment of NO₃⁻-N and NH₄NO₃ (P<0.01). Lastly, the light saturation point was above 1,000 μmol·m⁻²·s⁻¹ for NO₃⁻-N and NH₄NO₃ treatments, and around 600 μmol·m⁻²·s⁻¹ for the NH₄⁺-N treatment.

**Figure 1.** Responses of chlorophyll fluorescence parameters $F_v/F_m$, $\Phi_{PSII}$, $q_p$ and NPQ in the leaves of mulberry seedlings to different nitrogen forms. Means ± SD of three replicates are presented. Values followed by different small letters mean significant difference (p<0.05), values followed by different capital letters mean very significant difference (p<0.01). n=3

**Figure 2.** Responses of chlorophyll fluorescence parameters of mulberry seedling leaves to illumination intensity under the treatment of different nitrogen fertilizer treatments. Means ± SD of three replicates are presented. n=3
**Responses of OJIP curves in leaves of mulberry seedlings to different nitrogen forms**

Fig. 3-A shows that there were significant differences in terms of the OJIP curves of mulberry leaves under the treatments of different nitrogen forms. We did not observe a difference in the relative fluorescent intensities at the O and J step on the OJIP curve in plants treated with NO$_3^-$-N and NH$_4$NO$_3$. With the extension of time, the relative fluorescent intensities of mulberry leaves at the I and P step under the treatment of NH$_4$NO$_3$ gradually became lower than those treated with NO$_3^-$-N. Under the NH$_4^+$-N treatment, the relative fluorescent intensities of mulberry leaves at the O and J step were significantly higher than those treated with NO$_3^-$-N and NH$_4$NO$_3$, but at the P step, the relative fluorescence intensity was lower than those under the treatments of NO$_3^-$-N and NH$_4$NO$_3$.

![Figure 3](image_url)

**Figure 3.** Responses of OJIP curve and the standardized O-P, O-J and O-K curves in leaves of mulberry seedlings to different nitrogen forms. Chlorophyll a fluorescence transients were analyzed with the JIP-test

After standardization of the OJIP curve according to O-P, O-J and O-K, we observed that under the NH$_4^+$-N treatment, the relative variable fluorescences of the *M. alba* leaves at the J step (2 ms) and the I step (30 ms) were significantly increased compared to the NO$_3^-$-N and NH$_4$NO$_3$ treatments. Under the NH$_4$NO$_3$ treatment, the relative variable fluorescence of the mulberry leaves at the J step was slightly higher compared to the NO$_3^-$-N treatment, but there was no significant difference between the two treatments at the I step (Fig. 3-B). The relative variable fluorescence of the mulberry leaves at the K step (0.3 ms) was significantly higher in the NH$_4^+$-N treatment compared to NO$_3^-$-N and NH$_4$NO$_3$ treatments, while there was no significant difference between the NO$_3^-$-N and
NH₄NO₃ treatments (Fig. 3-C). There were no major differences in the standardized O-K curves between the different treatments, however, the relative variable fluorescence of the mulberry leaves at the L step (0.15 ms) was higher in the NH₄⁺-N treatment compared to the NO₃⁻-N and NH₄NO₃ treatments (Fig. 3-D).

**The effect of nitrogen forms on the variable fluorescence in the OJIP curve in mulberry seedling leaves**

We next conducted a quantitative analysis of the differences in the relative variable fluorescence at each point, and found that the relative variable fluorescence of \( V_L, V_K, V_J, \) and \( V_I \) of *M. alba* leaves at the L, K, J and I step were all significantly higher in the NH₄⁺-N treatment compared to the NO₃⁻-N and NH₄NO₃ treatments. The increases were 7.19% \((P>0.05)\), 29.97% \((P<0.01)\), 46.39% \((P<0.01)\) and 15.02% \((P<0.01)\), respectively, when compared to the NO₃⁻-N treatment, and 10.38% \((P>0.05)\), 31.43% \((P<0.01)\), 31.38% \((P<0.01)\) and 19.83% \((P<0.01)\) when compared to the NH₄NO₃ treatment (Fig. 4). All variables except for \( V_L \) showed highly significant differences. The differences of the relative variable fluorescence between the NO₃⁻-N and NH₄NO₃ treatments were relatively small. One notable difference was the 4.13% \((P<0.05)\) increase of \( V_I \) in the NO₃⁻-N treatment compared to the NH₄NO₃ treatment.

![Figure 4. Responses of \( V_L, V_K, V_J \) and \( V_I \) in leaves of mulberry seedlings to different nitrogen forms. Means ± SD of three replicates are presented. Values followed by different small letters mean significant difference \((p<0.05)\), values followed by different capital letters mean very significant difference \((p<0.01)\). n=3](image)

**Responses of \( S_m, N, \varphi E_o \) and \( \varphi D_o \) in leaves of mulberry seedlings to different nitrogen forms**

We observed significantly higher \( S_m \) and \( N \) in mulberry leaves in plants treated with NH₄⁺-N compared to the NO₃⁻-N and NH₄NO₃ treatments. The \( S_m \) and \( N \) were, slightly lower under the NH₄NO₃ treatment compared to the NO₃⁻-N treatment, but the difference was not significant (Fig. 5). Under the NH₄⁺-N treatment, the \( \varphi E_o \) of mulberry leaves were 54.27% \((P<0.01)\) lower compared to the NO₃⁻-N treatment, and 47.27% \((P<0.01)\) lower compared to the NH₄NO₃ treatment. The \( \varphi E_o \) of mulberry leaves was 15.30% \((P>0.05)\) higher under NO₃⁻-N treatment compared to the NH₄NO₃ treatment. Under NH₄⁺-N treatment, the \( \varphi D_o \) of mulberry leaves were 68.64% \((P<0.01)\) lower compared to the NO₃⁻-N treatment, and 54.11% \((P<0.01)\) lower compared to the NH₄NO₃ treatment. There was no significant difference in \( \varphi D_o \) between the NO₃⁻-N and NH₄NO₃ treatments.
Discussion

In our study, compared with the single nitrogen nutrition, the proper NH₄⁺-N:NO₃⁻-N ratio can promote mulberry growth. There are great differences in the uptake and utilization of nitrogen forms in plants, and the uptake of nitrogen is different in different plants or in different growth stages of the same plant. The pure supply of NH₄⁺-N will inhibit the absorption of K⁺ and Ca²⁺, and bring ammonia toxicity, limiting the growth of plants (Gruffman et al., 2012; Liu et al., 2019; Khan et al., 2020). However, the pure supply of NO₃⁻-N tends to increase the pH of rhizosphere, which is not conducive to the absorption and utilization of mineral nutrients (Ipperisiel et al., 1989; Guo et al., 2017; Cai et al., 2019). Combined with the results of previous studies and our study, the reasons for the highest growth of mulberry when the ratio of NH₄⁺-N and NO₃⁻-N was 50:50 were as follows: on the one hand, it was conducive to root growth, increased the absorption and transformation of soil nutrients, and reduced ammonia poisoning (Omara, 1989; Zhang et al., 2019; Yang et al., 2020); On the other hand, under the condition of solution culture, ammonium nitrogen will not be quickly converted to nitrate nitrogen, which not only avoids the reduction of cation absorption under the condition of single ammonium nitrogen supply, but also avoids the low nitrogen utilization rate caused by the easy leaching of NO₃⁻-N in soil culture, which can save more energy and increase the absorption of phosphorus than single nitrate nitrogen. Therefore, mulberry grows best when NH₄⁺-N and NO₃⁻-N are properly proportioning.

Chlorophyll fluorescence analysis is important in understanding the absorption and utilization of light energy by plants, and the function of the photosynthesis system. The effects of different nitrogen forms on a plant’s photosynthesis system can be different. For example, the study by Chen et al. showed that rice plants under water-stress had less inhibitory effect on the photosynthetic capability when treated with NH₄⁺-N compared to the plant treated with NO₃⁻-N, and the content of Rubisco in the leaves was higher (Sun et al., 2003; Chen et al., 2006; Guo et al., 2017; Yang et al., 2020). Here, we found that treating M. alba with NH₄⁺-N resulted in significantly decreases in Fv/Fm, ΦPS II and qP in the leaves compared to the NO₃⁻-N treatment. From the illumination response curves of the chlorophyll fluorescence parameters, we also observed that mulberry leaves under different light intensities result in significantly lower ΦPS II and ETR in the NH₄⁺-N treatment compared to NO₃⁻-N. Under the treatment of NH₄⁺-N, the ETR light saturation point was significantly lower than those under the treatment of NO₃⁻-N. This suggests that
treating mulberry with NH$_4^+$-N reduces the PS II photochemical activity and solar energy utilization capacity of the _M. alba_ leaves compared to NO$_3^-$-N treatment. Interestingly, we observed significantly higher NPQ in _M. alba_ leaves treated with NH$_4^+$-N, indicating that the leaves of _M. alba_ treated with NH$_4^+$-N depended on the non-radiative energy dissipation mechanism of the xanthophyll cycle to reduce the excess excitation energy in leaves. However, this would also reduce the proportion of light energy used in photochemical reactions under NH$_4^+$-N treatment, thus directly leading to a reduced supply of the assimilatory power such as ATP and NADPH, and further inhibiting the photosynthetic carbon assimilation ability, thereby reducing the amount of photosynthate accumulation. This is consistent with the results obtained by a large number of studies showing that application of NH$_4^+$-N alone can have a toxic effect on plants (Britto et al., 2001; Cai et al., 2017; Mu et al., 2021).

In addition, rational application of NH$_4^+$-N and NO$_3^-$-N can significantly mitigate ammonium salt poisoning in plants. The study by Jan et al. showed that, compared to the application of NO$_3^-$-N alone, a mixed application of NH$_4$ $^+$-N and NO$_3^-$-N can significantly increase dry matter accumulation and protein content in plants (Jan et al., 2013; Mu et al., 2021). However, the study by Nathawat et al. found that a mixed application of NH$_4^+$-N and NO$_3^-$-N, the yield of _Brassica juncea_ L. seeds showed no difference compared to single application of NO$_3^-$-N, but was significantly higher than a single application of NH$_4^+$-N (Nathawat et al., 2007; Yang et al., 2019). A mixed application of NH$_4^+$-N and NO$_3^-$-N can also benefit the growth of _Citrus reticulata_ (Nathawat et al., 2007; Cai et al., 2017). In this study, we found that chlorophyll fluorescence parameters of mulberry leaves were significantly higher in NH$_4$NO$_3$ treated plants compared to NH$_4^+$-N, but showed no significant difference compared to NO$_3^-$-N treatment. The treatment of NH$_4$NO$_3$, which is equivalent to a treatment with 1 : 1 ratio mix of NH$_4^+$-N and NO$_3^-$-N, can significantly relieved ammonium salt poisoning in _M. alba_, and achieve an equimolar treatment level as NO$_3^-$-N.

The fast chlorophyll fluorescence kinetics technologies can qualitatively and quantitatively measure the functions of different sections of the photosynthesis process, and it is very important for the in-depth study on the photosynthetic function of plants. In this study, we observed significant differences in the OJIP curves between the different nitrogen treatments. Under the NH$_4^+$-N treatment, the relative fluorescence intensities of the mulberry leaves at the O and J step were significantly higher compared to NO$_3^-$-N and NH$_4$NO$_3$, but at the P step, the relative fluorescence intensities were lower than those under the treatments of NO$_3^-$-N and NH$_4$NO$_3$. Therefore, the NH$_4^+$-N treatment resulted in a less pronounced OJIP curve, which suggests that the PSII reaction center was less active. However, OJIP curve can be strongly influenced by environmental factors, and OJIP curves offend require standardization. In this study, we standardized the OJIP curve as O-P, O-J and O-K respectively, and under the NH$_4^+$-N treatment, the relative variable fluorescences $V_i$ and $V_q$ at the J step (2 ms) and I step (30 ms) were significantly increased compared the NO$_3$-N and NH$_4$NO$_3$ treatments. Under the NH$_4$NO$_3$ treatment, the relative variable fluorescence of the mulberry leaves at the J step was slightly higher than those under the treatment of NO$_3^-$-N, while there was no significant difference between the two treatments at the I step. $V_i$ reflects the situation of electron transfer from QA to QB at the receptor side of the PSII reaction center. Increased relative variable fluorescence at the I step caused by the inhibition of the transport process from QA to QB (Zhang et al., 2018a,b). Therefore, the results from this experiment showed that treating mulberry with NH$_4^+$-N reduced the capacity of electron transport from QA to QB at the receptor side of...
the PSII reaction center compared to treatments of NO$_3^-$-N and NH$_4$NO$_3$. However, under the treatment of NH$_4^+$-N, the $S_m$ and N of mulberry leaves were significantly higher, indicating that the PQ pool at the receptor side of the PS II reaction center was larger, and QA$^-$ was reduced more often. These also indicate that the low QA to QB transport capacity under the treatment of NH$_4^+$-N results from decreased electron acceptability of QB in the mulberry leaves, and not because of a reduced capacity to accept electrons by the PQ pool downstream of the electron transport. The relative instability of the QA function of mulberry leaves has been shown in previous experiments (Xu et al., 2012; Liu et al., 2019).

Under NH$_4^+$-N treatment, the relative variable fluorescence $V_K$ of the mulberry leaves at the K step (0.3 ms) was significantly higher than those under the treatments of NO$_3^-$N and NH$_4$NO$_3$, and there was no significant difference between the NO$_3^-$N and NH$_4$NO$_3$ treatments. This suggests that under the NO$_3^-$N and NH$_4$NO$_3$ treatments, the oxygen-evolving complex (OEC) activities of mulberry leaves were significantly higher than the NH$_4^+$-N treatment. High OEC activity facilitates the water splitting function at the donor side and provides sufficient electron supply for the photosynthetic electron transport chain. Low OEC activity in mulberry leaves under the NH$_4^+$-N treatment can lead to incomplete water splitting, resulting in the production of active oxygen molecules such as H$_2$O$_2$, thus undermining the normal function of the photosynthetic system. The decrease in the capacity of accepting electrons by QB at the electron transport receptor side may be caused by the attack by active oxygen molecules. NH$_4^+$-N treatment can change the ultrastructure of Lycopersicon esculentum leaf cells, and cause chloroplast swelling, fuzzy or even broken layers, and significant accumulation of osmiophilic granules. In contrast, treatment of NH$_4$NO$_3$ can significantly improve this situation (Zhang et al., 2012a, 2018a,b). The osmiophilic granule is an important sign of the dissociation of the thylakoid membrane (Zhang et al., 2012b, 2018; Penella et al., 2014). We found that the differences of the standardized O-K curves under different treatments were relatively small, but under the NH$_4^+$-N treatment, the relative variable fluorescence $V_L$ at the L step (0.15 ms) was higher than those under the NO$_3^-$N and NH$_4$NO$_3$ treatments. These results suggest that NH$_4^+$-N treatment alone results in lower structural stability of the thylakoid membrane of the mulberry leaf compared to NO$_3^-$N and NH$_4$NO$_3$ treatments. However, the variation ranges of $V_L$ under different treatments were all significantly smaller than those of $V_K$, $V_I$ and $V_J$, indicating that the stability of the thylakoid structure of mulberry leaves is less vulnerable to damage under the treatments of different nitrogen comparing to the OEC activity and the electron transfer function at the receptor side of the PSII reaction center.

Conclusions

The PSII photochemical activity of the mulberry leaves was significantly higher in the NO$_3^-$-N treatment compared to NH$_4^+$-N, and applying NH$_4^+$-N alone was toxic to mulberry. It not only reduced the PSII photochemical activity and the electron transport capacity in the leaves, but also inhibited the oxygen evolving complex function. The light energy absorbed by leaves was mainly dissipated in the form of invalid heat energy. The proportion of the light energy used in photochemical reaction was decreased, and even the thylakoid structure was altered in the NH$_4^+$-N treatment. However, under the treatments of NO$_3^-$N and NH$_4$NO$_3$, the photosynthetic capacity of mulberry leaves was significantly higher than the NH$_4^+$-N treatment. There was no significant difference between the NO$_3^-$N and NH$_4$NO$_3$ treatments; and the treatment of NO$_3^-$-N could...
significantly relieve the ammonium toxicity in mulberry caused by applying NH$_4^+$-N alone. Our results provide the basis for the development of new nitrogen fertilizer utilization schemes for M. alba. In order to further explain the decline of photosynthetic mechanism capacity, especially chlorophyll fluorescence, the enzymatic induced by sole nitrogen forms, but this needs further study.

**Funding.** This study was financially supported by China-Norway International Collaboration Project (Grant No.CHN-17/0019); The project of Heilongjiang Province Key Laboratory of Cold Region Wetland Ecology and Environment Research (No.201910) of the Harbin University; Young Doctoral Research Foundation of Harbin University (No.2020106); Harbin University of Dr Youth “Internet + double gen start-up fund project” (HUSC202108).

**REFERENCES**


