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Effects of Foliar Application of Magnesium Fertilizer on Photosynthesis and Growth in Grapes

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Abstract: Efforts to increase grape yields have focused on using nitrogen, phosphorus, and potassium fertilizers, often causing unintended magnesium (Mg) deficiencies. To overcome Mg deficiency, different concentrations of $MgSO_4 \cdot 7H_2O$ (0, 1, 2, 3, 4 mM) and GABA (2.5 mM), as foliar sprays, were applied during the fruit enlargement and color transition stages. Key physiological parameters such as leaf growth, photosynthesis, and chlorophyll fluorescence were assessed. Interestingly, foliar Mg application increased the key physiological parameters, with the 3 mM treatment (M3) delivering the best improvement. Compared to the control, the M3 treatment increased dry weight and leaf area by 35.9% and 37.2%, respectively. Specifically, the foliar Mg application (M3) improved the photosynthesis (Pn), transpiration (Tr), and stomatal conductance (gs) of leaves when compared to the control. Additionally, the foliar Mg application improved the PSII photosynthetic efficiency, electron yield, and electron transport rates, following the order M2 > M3 > M1 > M0 > M4. This study demonstrated the essential role of foliar-applied Mg, with GABA, in improving grape physiology. Interestingly, the curve-fitting analysis of foliar Mg concentration and grape yield identified 2.14 mM of Mg as the optimal concentration for promoting grape growth.

Keywords: *Vitis*; gas exchange; nutrient deficiency; GABA; PSII electron transport; yield

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1. Introduction

Grapes (*Vitis vinifera* L.) are one of the oldest cultivated fruit species in the world [1], and they are well known for their considerable economic importance. As of 2023, global grape production stands at around 78 million tons, with the majority used for wine production, followed by table grapes and raisins. The grape industry plays a vital role in rural revitalization and targeted poverty alleviation, supporting the livelihoods of millions of farmers and agricultural workers globally, especially in traditional wine-producing areas. In recent years, efforts to boost crop yields increasingly focused on using nitrogen, phosphorus, and potassium fertilizers, while magnesium (Mg) fertilization was often neglected. This unintended nutritional neglect has led to Mg depletion in soils, causing physiological issues and lowering fruit quality. Research has shown that Mg deficiency disrupts sugar accumulation and organic acid metabolism, leading to lower fruit sweetness and higher acidity [2], negatively affecting grape storage, transportation, and marketing.

Magnesium, an essential element for plant growth [3], plays a vital role throughout the entire life cycles of plants [4]. In plant growth, magnesium is a crucial component of the chlorophyll molecule [5]. Chlorophyll serves as the "energy factory" of plants, responsible for absorbing light energy during photosynthesis. Magnesium is a key component in this factory; without it, chlorophyll synthesis is significantly hindered [6,7]. With adequate magnesium, plant leaves can effectively perform photosynthesis, continuously converting carbon dioxide and water into organic compounds like glucose, thus providing the necessary energy and materials for plant growth. Additionally, Mg acts as an activator of various enzymes [8] and participates in numerous physiological and biochemical reactions in plants, including cell division and protein synthesis. During ripening, magnesium is transferred to the fruit; magnesium deficiency can lead to uneven fruit size, reduced sweetness, and color deterioration, adversely affecting the market value of crops. Magnesium ions help to maintain the structural stability of the chlorophyll–protein complexes [9,10]. The thylakoid membrane of chloroplasts contains various chlorophyll–protein complexes, including photosystem I (PSI) and photosystem II (PSII) [11,12]. The chlorophyll molecules in these complexes efficiently capture light energy, while the presence of Mg ions ensures their structural integrity, thus enhancing light energy capture efficiency [13,14]. Previous studies indicate that magnesium deficiency severely restricts the structure and function of PSI and PSII [15]. For example, Mg deficiency was observed to reduce Fv/Fm in citrus seedlings, whereas it did not affect Fv/Fm or other fluorescence indicators in sunflower plants [16]. Magnesium is a key component in the carbon dioxide assimilation process [4,17]. Scientific evidence indicates that magnesium deficiency negatively impacts the function of ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco), an enzyme involved in the carbon dioxide fixation process [18], leading to reduced photosynthetic efficiency in plants [19]. Additionally, supplementing magnesium fertilizer to magnesium-deficient crops can significantly enhance their photosynthetic capacity. During the boot stage of crops, higher canopy photosynthesis after flowering can be maintained through the foliar application of magnesium sulfate, as confirmed in studies on maize [20,21]. Chlorosis in crops is a clear indication of magnesium deficiency, typically signaling a significant decrease in yield due to disrupted sugar transport from production sites to storage organs, along with reduced biomass accumulation in roots and reproductive tissues [22]. Previous studies have indicated that Mg fertilization improves the yield and fruit quality of crops such as 'Washington navel orange', bananas, and hazelnuts in Turkey [23,24]. From the chemical perspective, Mg ions have large hydration radii, weak adsorption of soil colloids, and are susceptible to leaching, especially in acidic soils with low cation exchange capacity [25]. Therefore, the strategy of using soil Mg application is not ideal, and the utilization rates of Mg fertilizer from the soil to the roots are low. Thus, foliar Mg fertilization provides a new and effective way of delivering nutritional supplements. A search of the literature revealed that foliar fertilization of crops has many advantages, such as rapid nutrient absorption, better fertilizer efficiency, a high nutrient utilization rate, effective dilution management, avoidance of nutrient degradation, a reduction in environmental pollution, and greater resilience under unfavorable conditions [26]. An earlier study using foliar Mg application to improve the fruit color, quality, and yield of the grape variety "Crimson seedless" was reported [27].

γ-aminobutyric acid (GABA), the only well-defined ion transport regulator, can regulate plant uptake of key elements and significantly improve fertilizer utilization [28]. It was found that GABA increased plant uptake of Mg by 57% [29]. Foliar GABA treatment on pomegranate trees (variety 'Mollar de Elche') increased crop yield and delivered a deeper red color to the fruit skins and arils [30]. The application of nitrogen fertilizer combined with GABA significantly increased the average grain yield of rice, enhanced the growth of rice plants, and improved the utilization rate of nitrogen fertilizer [31].

Applying GABA or Mg individually was effective in improving stress resilience and restoring yield and quality [32,33], but it is still unknown whether the combined application of GABA and Mg has additive and positive effects. Therefore, studying the effects of GABA+Mg on physiology is essential for improving grape yield and quality. The main objectives of this study were as follows: (1) to assess the effects of various concentrations of GABA+Mg on the growth and photosynthetic performance of magnesium-deficient grapes; (2) to evaluate the effects of different GABA+Mg concentrations on plant light use efficiency and PSII activity using fluorescence probe technology; (3) to determine the optimal foliar application concentration of GABA+Mg for improving grape yield.

2. Materials and Methods

2.1. Plant Material and Treatments

The experiment was carried out in the Hongqi Town Horticultural Vineyard Solar Greenhouse, Bayuquan District, Yingkou City, Liaoning Province, China, located in the southern part of the Liaodong Peninsula (122.15° E, 40.23° N). The climate of the region belongs to the warm temperate sub-humid climate zone with an annual average temperature of 9.6 °C, annual precipitation of 580 mm, annual sunshine hours of 3000 h, and a frost-free period of 172–188 days. This region is considered to be the optimal zone for grape cultivation. The basic agrochemical characteristics of the soil are shown in Table 1. The grape (*Vitis vinifera* L.) variety tested was Queen Nina (Queen An Yun × 20 An Yunjin). In this experiment, a single-factor randomized block design was used. In addition to the control (CK), there were four treatments: M1, M2, M3, and M4. The concentrations of magnesium sulfate were 0 mM (control), 1 mM (M1), 2 mM (M2), 3 mM (M3), and 4 mM (M4), and the concentration of GABA was 2.5 mM across all treatments including the control. Each treatment had 3 replicates. Magnesium fertilizer was applied to the leaf surface four times during the fruit expansion and color transformation period (103 days). The fertilizer was uniformly applied to the leaf surface, restricted to the point of runoff: after 4:00 PM on a sunny day when the vineyard (under protected cultivation) temperatures ranged from 28 to 30 °C and relative humidity levels were between 23% and 25%.

Table 1. The agrochemical characteristics of the soil before the establishment of the trial.

Depth (cm)	0–20	20–40
pH	6.14 ± 0.01	6.46 ± 0.01
Organic matter (%)	0.54% ± 0.01	0.38% ± 0.01
Alkaline hydrolysis nitrogen (mg/kg)	75.73 ± 1.75	62.00 ± 1.00
Effective phosphorus (mg/kg)	137.40 ± 2.28	130.35 ± 0.57
Rapidly available potassium (mg/kg)	1215.51 ± 28.98	2104.97 ± 35.18
Exchangeable Mg (g/kg)	0.46 ± 0.01	0.30 ± 0.01
Exchangeable Ca (g/kg)	5.25 ± 0.01	3.61 ± 0.01

2.2. Determination of Leaf Area, Leaf Extensibility, and Dry Weight

During the fruit color transition period, the leaves at the fruit setting site were selected, and 8 leaves were collected for each treatment. Then, the photos were imported into ImageJ (V. 1.53) software to measure leaf area and leaf elongation [34]. Subsequently, the collected leaves were washed with pure water to remove the residual fertilizer on the leaf surface, placed in a kraft paper bag, and killed at 105 °C for 30 min in a constant temperature blast drying oven (constant temperature blast drying oven, DHG-9204A, Shanghai, China). We dried the leaves to constant weight at 65 °C, using a one-thousandth precision electronic balance to measure the dry matter weight of each treated leaf and record parameters [35].

2.3. Determination of Chlorophyll Index and Gas Exchange Measurements

The net photosynthetic rate (Pn), stomatal conductance (gs), intercellular CO_2 concentration (Ci), and transpiration rate (Tr) were measured using a portable photosynthesis system (Li-6400XT, Licor Inc, Lincoln, NE, USA) from 9:00 to 11:00. The light intensity was set to 1500 μmol $m^{-2} \cdot s^{-1}$ [36]. The foliar chlorophyll index was determined non-destructively by a hand-held multi-parameter optical sensor (Multiplex, FORCE-A, Orsay, France).

2.4. Determination of Fast Fluorescence Rise Curve OJIP and the JIP-Test

The fast fluorescence rise curve OJIP was measured using the multifunctional plant efficiency analyzer M-PEA-2 (Hansatech, Pentney, UK). In each treatment, three leaves were measured and repeated three times. Before the determination, the leaves needed to be dark-adapted for 30 min. The intensity of saturation pulse light was set as 3000 μmol·quanta·m^{-2}·s^{-1} and the irradiation time was 2 s [36].

Based on the theory of energy fluxes in biomembranes, an analysis of the fast OJIP fluorescence rise has been developed, called the JIP-test, which links the different steps and phases of the transient with the redox states of PSII and, concomitantly, with the efficiencies of electron transfer in the intersystem chain and the end electron acceptors at the PSI acceptor side [37]. The analysis parameters are shown in Table 2.

Table 2. The definition of terms of the JIP-test parameters from the chlorophyll fluorescence transient OJIP emitted by dark-adapted leaves. Modified by [38].

Fluorescence Parameters	Description
F_0	Minimum fluorescence at 20 ms (all RCs were supposed to be opened)
F_V	Variable fluorescence ($F_m - F_0$)
F_m	Maximum fluorescence intensity at the P phase of OJIP (maximum RCs are supposed to be closed)
F_V/F_m	Maximum quantum yield of PSII
F_V/F_0	Efficiency of electron donation to PSII
V_J	Relative variable fluorescence at the J-step
Area	The area between the fluorescence curve and F_m
Φ_{Po}	Maximum quantum yield of primary photochemistry (t = 0)
ψ_0	The probability that the trapped electron was transferred to ETC beyond Q_A
Φ_{Eo}	Quantum yield of electron transported to ETC beyond Q_A
Φ_{Ro}	Quantum yield for the reduction in end electron acceptors at the PSI acceptor side (RE)
σ_{Ro}	Efficiency/probability with which an electron from the intersystem electron carriers moved to reduce end electron acceptors at the PSI acceptor side (RE)
ABS/RC	Absorption per reaction center at PSII/ratio of active reaction centers in PSII
DI_0/RC	Dissipation energy flux per reaction center (t = 0)
TR_0/RC	Trapped energy flux per reaction center (t = 0)
ET_0/RC	Electron transport flux per reaction center (t = 0)
PI_{ABS}	Performance index on absorption basis

2.5. Determination of the Yield

During the grape harvest period, three trees were selected for each treatment, and the fruits were harvested carefully.

2.6. Statistical Analyses

SPSS19.0 (Chicago, IL, USA) software was used for one-way analysis of variance (ANOVA), and the post hoc Duncan method (at $p < 0.05$) was used to test the significance of differences between treatments at each time point. Significant differences between treatments were indicated using lowercase letters. Values presented were the means ± one standard error (SE) of three replicates. All graphs were plotted and generated using Origin 8.0 software.

3. Results

3.1. Leaf Growth

The foliar application of magnesium fertilizer significantly increased the dry weight and leaf area of leaves in each treatment (Figure 1A,B). Among them, the M3 treatment had a significant effect compared with other treatments. Compared with CK, the dry weight and leaf area of M3 treatment increased by 35.9% and 37.2% ($p < 0.05$), respectively. Compared with M3, M4 treatment decreased by 16.3% and 11.8% ($p < 0.05$), respectively, indicating that the appropriate application of magnesium fertilizer promoted leaf growth but excessive application inhibited it. The leaf elongation rate of each treatment was not significantly different from that of CK (Figure 1C). The foliar spraying of magnesium fertilizer also increased the chlorophyll index (Figure 1D). The chlorophyll index of M2 treatment was significantly higher than that of CK treatment, which increased by 60.7% ($p < 0.05$) compared with CK. The chlorophyll indexes of the M3 and M4 treatments were significantly lower than that of CK treatment, as they decreased by 3.1% and 16.9% ($p < 0.05$), respectively. It shows that the chlorophyll index is the best when the concentration of foliar application reaches 2 mM, and excessive application will cause the chlorophyll index to decrease.

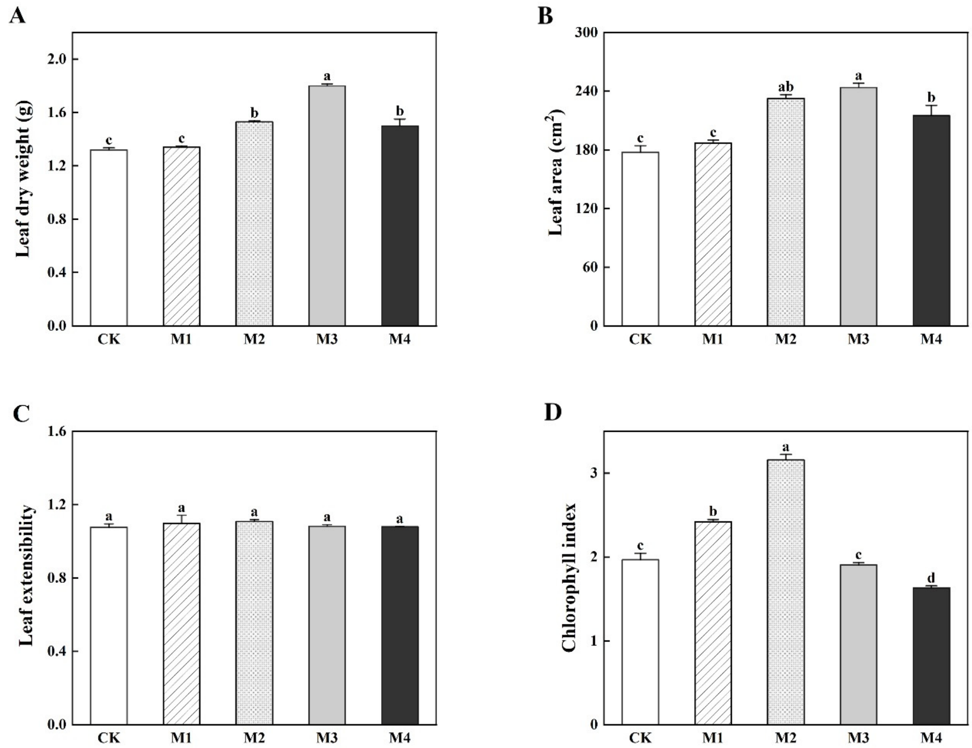

Figure 1. The effects of the foliar application of different concentrations of magnesium fertilizer on the leaf dry weight (**A**), leaf area (**B**), leaf elongation (**C**), and chlorophyll index (**D**) of grape. Values are means ± SD (n = 3). Different letters indicate significant differences according to Duncan's multiple range tests ($p < 0.05$).

3.2. Photosynthetic Parameters

The application of magnesium fertilizer increased Pn, Tr, and g_s, while Ci decreased. The Pn, Tr, and g_s of M3 were significantly higher than those of other treatments, which increased by 48.8%, 74.1%, and 33.1% ($p < 0.05$), respectively, compared with CK. Compared with CK, M2 treatment increased by 9%, 35%, and 6.2% ($p < 0.05$), respectively. M1 did not significantly increase; M4 treatment decreased by 3.3%, 16.6%, and 14.7% ($p < 0.05$), respectively, compared with CK, indicating that the excessive application of magnesium fertilizer would lead to decreases in Pn, Tr, and g_s. The Ci of M3 was the lowest, which was 11.4% ($p < 0.05$) lower than that of CK treatment, and there was no significant difference between other treatments (Figure 2).

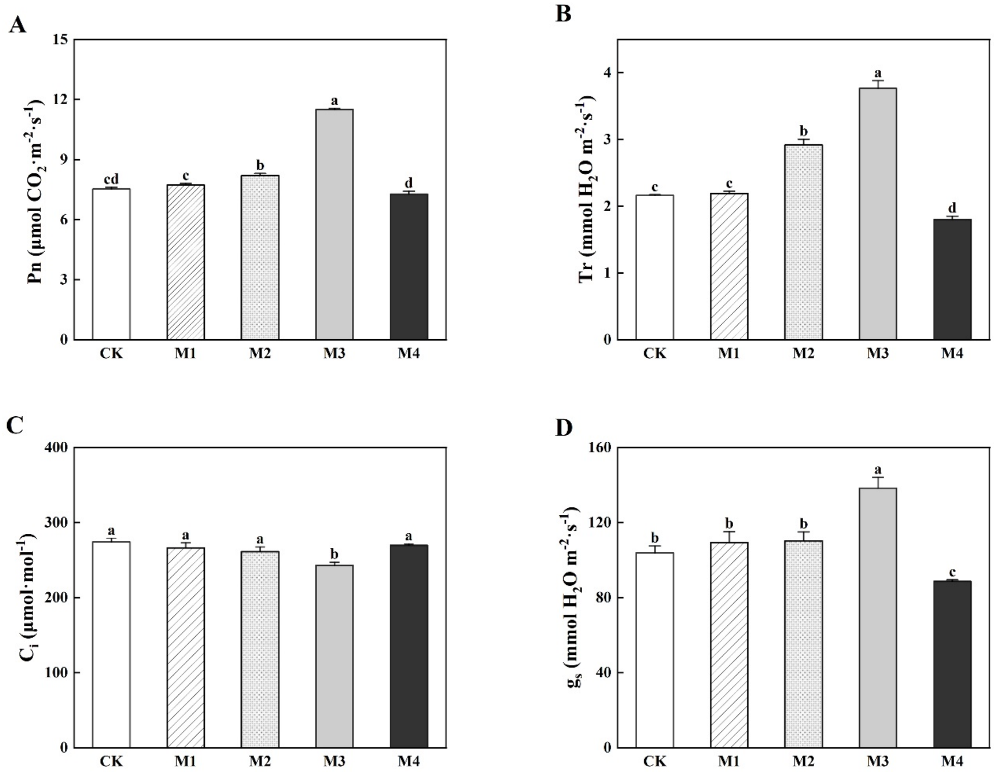

Figure 2. The effects of the foliar application of different concentrations of magnesium fertilizer on foliar gas exchange parameters [net photosynthetic rate (Pn, (**A**)), transpiration rate (Tr, (**B**)), intercellular CO_2 concentration (Ci, (**C**)) and stomatal conductance (g_s, (**D**))] of grape. Values are means ± SD (n = 3). Different letters indicate significant differences according to Duncan's multiple range tests ($p < 0.05$).

3.3. The OJIP and JIP-Tests

In order to further explore the effect of the foliar application of magnesium fertilizer on the PSII donor side and acceptor side of grape leaves, this experiment analyzed the fast chlorophyll fluorescence induction kinetics curve (OJIP) of grape leaves under different concentration treatments and standardized it (Figure 3A,C,E) to analyze the changes at each point. Figure 3B,D,F are the OJIP curve values of each treatment leaf minus the corresponding values of CK treatment.

Compared with CK, M1, M2, and M3 treatments all led to decreases in J and I in grape leaves, among which the M3 treatment was the lowest, while the M4 treatment led to increases in J and I. The increases in J and I reflected the limitation of Q_A to Q_B electron transport in the photosynthetic electron transport chain (During the transfer of electrons from QA to QB, the energy from the electrons is used to pump protons across the thylakoid membrane, creating a proton gradient within the thylakoid lumen. This proton gradient serves as the energy source for ATP synthesis during photosynthesis), the excessive reduction on the PS II receptor side, and the degradation of the D1 protein in PS II [39]. The above results showed that compared with CK, the appropriate application of magnesium fertilizer could accelerate the electron transport from Q_A to Q_B in the photosynthetic electron transfer chain, and the electron transfer rate was M3 > M2 > M1. However, when the concentration of foliar application of magnesium fertilizer was too high, the electron transfer from Q_A to Q_B in the photosynthetic electron transport chain was limited, and the PS II acceptor side was over-reduced (Figure 3A,B). K reflects the damage degree of the oxygen-evolving complex (OEC) at PSII, and L reflects the damage degree of the chloroplast thylakoid membrane. Compared with CK, the K and L steps were further reduced in M1, M2, and M3, indicating that appropriate foliar application of magnesium fertilizer could slow down the damage of oxygen-evolving complex (OEC) and the degradation of the thylakoid membrane, and the degree of mitigation was M3 > M2 > M1. However, M4 increased at K and L compared with CK, indicating that excessive application of magnesium fertilizer could lead to OEC damage and chloroplast thylakoid membrane damage, which destroyed the integrity of chloroplasts (Figure 3C–F).

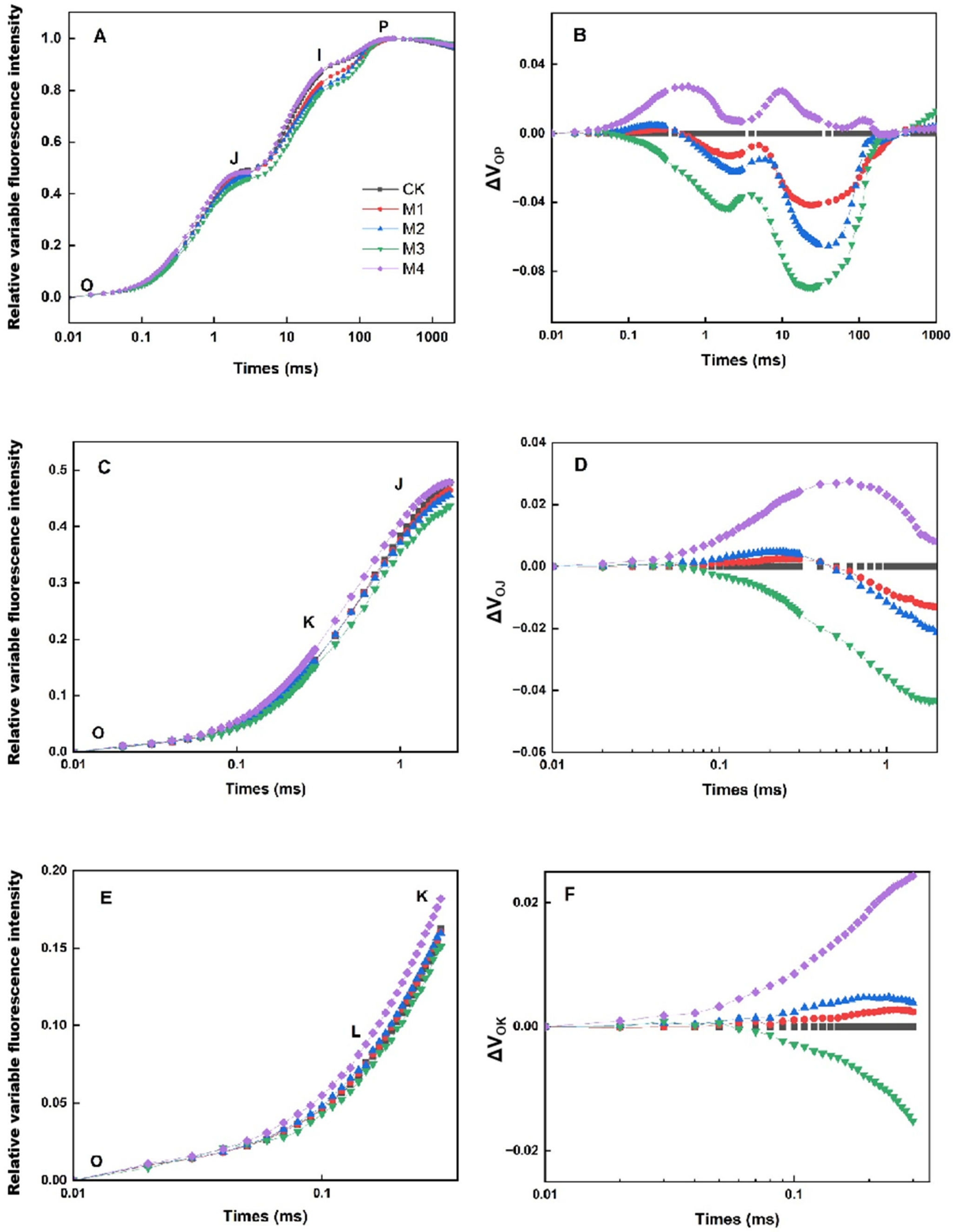

Figure 3. The effects of the foliar application of different concentrations of magnesium fertilizer on chlorophyll fluorescence OJIP curves in grape leaves: (**A**) normalized OJIP transient; (**B**) ΔVt was obtained by subtracting the untreated leaf dynamics from the leaf dynamics treated with magnesium fertilizer between O and P; (**C**) normalized transient between O and J; (**D**) ΔVt was obtained by subtracting the untreated leaf dynamics from the leaf dynamics treated with magnesium new fertilizer between O and J; (**E**) normalized transient between O and K; (**F**) ΔVt was obtained by subtracting the untreated leaf dynamics from the leaf dynamics treated with magnesium new fertilizer between O and K. O indicates the O step at about 20 ms; J indicates the J step at about 2 ms; I indicates the I step at about 30 ms; P indicates the P step; K indicates the maximum fluorescence.

Quantitative analysis of OJIP transients is called the 'JIP-test'. The values of the chlorophyll fluorescence parameters were normalized to those of the control plants and plotted as spider plots (Figure 4). The deviation of the behavior pattern of grape leaves treated with different concentrations and the control grape leaves demonstrates the effect of each treatment on each parameter.

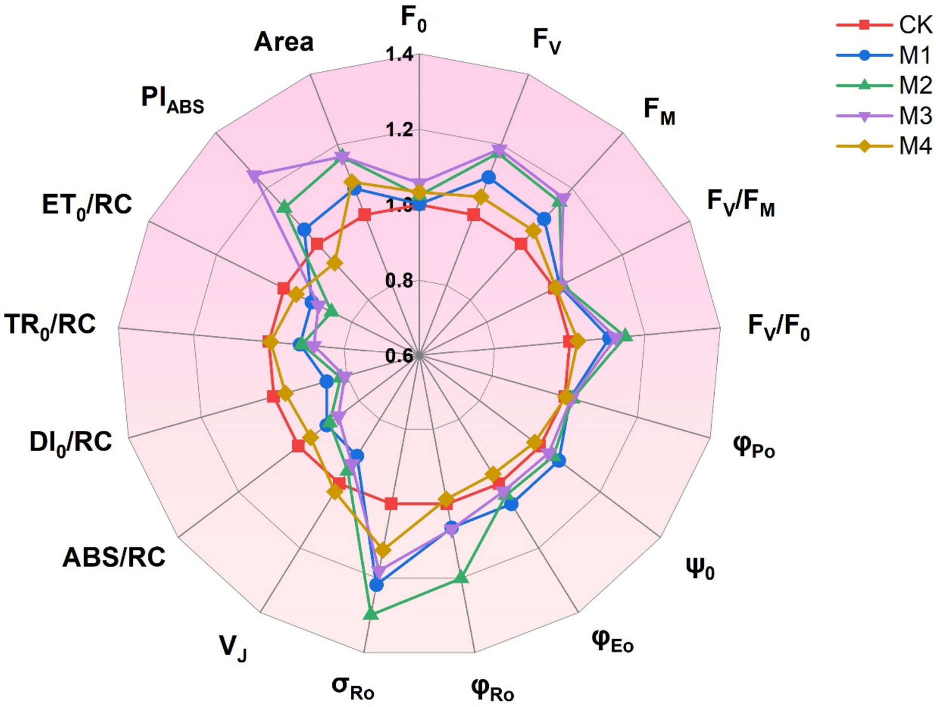

Figure 4. A spider plot of selected JIP parameters derived from chlorophyll fluorescence in each treatment.

We observed that PI_{ABS} calculated on an absorption basis increased significantly when 1~2 mM magnesium fertilizer was applied to the leaves. PI_{ABS} is a comprehensive parameter that considers different phenomena associated with PSII photochemical activity. The results showed that M2 increased by 13% compared with CK, M3 increased by 24.8% compared with CK, and M4 decreased. Compared with CK, the maximum quantum yield of PSII (F_V/F_m) and the PSII reaction center activity (F_V/F_0) of M1, M2, and M3 treatments were significantly increased under the application of magnesium fertilizer. Among them, M2 increased the most, increasing by 2.1% and 14.7%, respectively, with an order of M2 > M3 > M1, with no significant difference ($p < 0.05$). However, M4 decreased by 1.4% and 9% ($p < 0.05$) compared with M3, indicating that excessive concentrations of Mg fertilizer aggravated the photoinhibition of grape plants. The analysis results showed that M2 has the lowest V_J, indicating that M2 has the fastest electron transfer rate.

Similarly, the application of Mg fertilizer increased the maximum quantum yield of primary photochemistry (φPo), the quantum yield of electron transport to ETC beyond Q_A (φEo), the quantum yield for the reduction in end electron acceptors at the PSI acceptor side (φRo), the efficiency/probability with which an electron from the intersystem electron carriers move to reduce end electron acceptors at the PSI acceptor side (σRo), and the efficiency of PSII to move trapped electrons in the electron transport chain (ψ_0). And the order was M2 > M3 > M1 > CK > M4. The increase in the above parameters will accelerate the capture of light energy and electron transfer by PSII, resulting in increases in PSII activity and light energy conversion efficiency. The results showed that M2 had the highest PSII activity and light energy conversion efficiency.

With the increase in Mg concentration, it was observed that the energy flux for the absorption (ABS/RC) of grape leaves decreased first and then increased. In contrast, the ABS/RC of M3 was the lowest, decreasing by 13.2% ($p < 0.05$), and the M4 was higher compared with M3, increasing by 10.7% ($p < 0.05$). Electron transport (ET_0/RC) also decreased first and then increased. The ET_0/RC of M2 was the lowest, decreasing by 14.1.5% ($p < 0.05$), and other treatments also decreased compared with CK. A reduction in dissipation energy flux per reaction center (DI_0/RC) was observed. Compared with the control, M3 decreased the most significantly, decreasing by 19.5% ($p < 0.05$). Similarly, it was found that the trapped energy flux per reaction center (TR_0/RC) decreased, with the most significant being M3, which was reduced by 12% ($p < 0.05$). It was plausible that the application of the GABA+Mg fertilizer increased the active reaction center RC, which led to the decrease in flux values.

3.4. Yield

Compared with CK, the yields of M1, M2, and M3 treatments increased by 8.2%, 32.3%, and 29.1% ($p < 0.05$), respectively (Figure 5A). There was no significant difference between M4 and CK, which decreased by 23% ($p < 0.05$) compared with M3, indicating that the optimum concentration for yield increase was between 2 mM and 3 mM. Therefore, we obtained the optimal concentration of Mg fertilizer for foliar application of 2.14 mM by fitting the curve (Figure 5B).

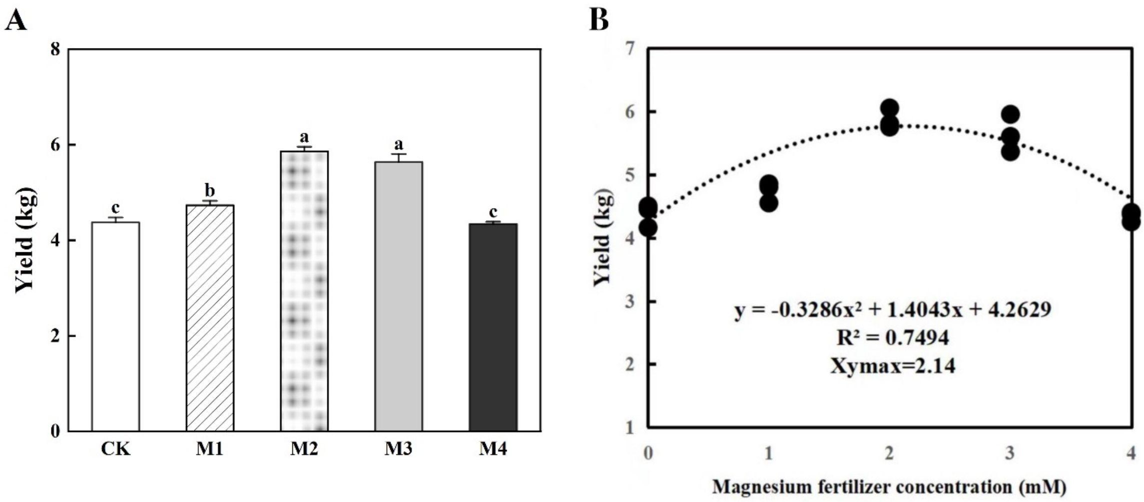

Figure 5. The effects of the foliar application of different concentrations of magnesium fertilizer on grape yield (**A**). The fitting diagram of yield along different magnesium (Mg) supplies in grape plants (**B**). Different letters indicate significant differences according to Duncan's multiple range tests ($p < 0.05$).

4. Discussion

4.1. Leaf Growth

As the main photosynthetic organs of plants, the growth status of leaves will directly affect the yield and quality of fruits. Magnesium (Mg) deficiency is known to reduce the growth and leaf area of crops, especially the newly developed leaves. The poor foliar development during Mg deficiency is related to vein lignification [40,41]. This study showed that compared with no Mg fertilizer, spraying Mg fertilizer (with GABA at 2.5 mM) on leaves could increase the dry weight and leaf area of grape leaves. With higher levels of Mg concentrations, it increased first and then decreased, and it reached the maximum value in the M3 treatment. These observations for grapes were in parallel with previous studies on apples and broad beans [42]. Magnesium is an important component of chlorophyll. Thus, Mg application can increase the chlorophyll content, photosynthetic rate, and nutrient accumulation, thereby promoting plant growth [43]. A large number of studies have found that foliar fertilization with $MgSO_4$ increases the chlorophyll concentration in the leaves of maize [44], soybean [45], and oregano [46]. In our study, the foliar application of GABA+Mg fertilizer also increased the chlorophyll index, reaching its peak in the M2 treatment. This may be due to the role of GABA in improving the absorption of Mg in grapes, leading to higher chlorophyll content. However, when the Mg levels exceed a certain threshold, GABA will act as a signaling molecule to reduce Mg uptake by interacting with either GABA receptors or the downstream signaling pathways.

4.2. Photosynthetic Parameters

Photosynthesis is the most important physiological process of plants and the most important chemical reaction on earth. This is also one of the most sensitive physiological processes of plants to various biotic and abiotic stresses [47]. Mg^{2+} is the central atom in the tetrapyrrole rings of both chlorophyll Chla and Chlb molecules in the chloroplasts, which makes it effective at gathering light for photosynthetic carbon reduction reactions [48]. Stomata is the main channel for gas exchange between plant leaves and the outside world, which controls the entry and exit of CO_2 and the transpiration of plant leaves, thus affecting the photosynthetic rate of plants [49]. The photosynthetic rate of plants is inhibited when Mg is deficient, which has been confirmed in citrus [50], sugarcane [51], banana [52], and other crops. In this study, it was found that by spraying an appropriate amount of GABA+Mg fertilizer, the Pn, g_s, and Tr of leaves were enhanced significantly, while Ci decreased. However, when the concentration of GABA+Mg fertilizer was too high, Pn, Gs, and Tr decreased. GABA can regulate stomatal closure [53], thereby influencing the net photosynthetic rate of leaves by modulating transpiration. When magnesium levels are low, GABA regulates the leaves to enhance magnesium uptake for photosynthesis. As magnesium levels increase, GABA reduces magnesium entry into cells by regulating stomatal activity and transpiration, preventing potential damage to crops from high magnesium levels. This is consistent with the findings on GABA's role in alleviating salt stress in cotton [54].

4.3. OJIP

The effects of different environments on photosynthesis can be effectively studied using chlorophyll fluorescence kinetics [55]. OJIP analysis is the most powerful and widely used technique for understanding the structural stability of PSII, as it gives a complete insight into energy fluxes between different components of PSII [56]. In this study, we observed that supplementing GABA+Mg fertilizer to leaves effectively reduced J and I, which showed that the electron transfer from Q_A to Q_B in PSII was smoother, the ability of PSII receptor side to receive and transport electrons was enhanced, and the activity of PSII complex core protein D1 protein was improved. At the same time, it also led to decreases in the K point and L point, which reflected the increase in OEC activity at PSII and slowed down the damage to the chloroplast thylakoid membrane. However, excessive use of GABA+Mg fertilizer will lead to an increase in the above stage.

4.4. Chlorophyll Fluorescence Parameters

The increase in F_V/F_0 indicated that the electron donation efficiency from OEC to PSII donor side increased [57]. The increase in F_V/F_m indicated that the light energy conversion efficiency of PSII increased. These results are similar to some early studies on bananas [46] and corn [21]. The total complementary area between the fluorescence induction curve and F_m is a tool used to represent the pool size of reduced plastoquinone on the reducing side of PSII [58]. The increases in area and F_m were due to the promotion of electron transfer rates from the reaction center to the quinone pool. PI_{ABS} is used as a measure of plant performance to quantify PSII behavior [59,60]. This study found that the appropriate application of GABA+Mg fertilizer increased the PI_{ABS} of grape leaves.

It is evident that during the experiment, the effects of GABA+Mg were also observed on the electron transport system. The results showed that the appropriate application of GABA+Mg fertilizer could promote the photosynthetic efficiency of PSII, which was manifested in the increases in the quantum yield of PSII electron transport and the efficiency of the capture excitation energy of the open PSII reaction center (φPo, φEo, φRo, ψ_0). σRo is called the efficiency with which an electron can move from the reduced intersystem electron acceptors to the PSI end electron acceptors. An increase in this parameter is associated with an increase in IP amplitude, which was shown to be a symptom either as an increase in PSI content [61] or an increase in PSI fraction involved in linear electron flow [62]. In our study, σRo also increased due to the application of GABA+Mg fertilizer. At the same time, the decrease in V_J also indicated that the application of GABA+Mg fertilizer accelerated the electron transfer of the PSII receptor side from Q_A to Q_B.

We wanted to understand whether the application of GABA+Mg fertilizer would change the ratio between the antenna light-harvesting complex (ABS) and the active PSII reaction center. The results showed that the appropriate application of GABA+Mg fertilizer could decrease the ABS/RC, and the decrease in ABS/RC implied that either a part of active RC was enhanced or the apparent antenna size was decreased [59,63]. This study speculated that the use of GABA+Mg fertilizer increased the active RC, resulting in a decrease in ABS/RC. The decrease in ABS/RC was accompanied by a decrease in the capture of each active reaction center (TR_0/RC). At the same time, the electron transport flux ET_0/RC of each reaction center decreased, while the energy dissipation DI_0/RC also decreased.

4.5. Yield

Finally, we analyzed the yields of grapes in each group and found that the appropriate application of magnesium fertilizer increased the yield of grapes, which was consistent with the effect of magnesium fertilizer on cotton [64], pomelo [65], navel orange [66], and other crops. The optimum concentration was determined by fitting the graph mathematically.

5. Conclusions

Our results demonstrated that foliar applications of Mg and GABA improved photosynthetic capacity and electron transfer rates in grapes, thereby enhancing dry matter accumulation and delivering higher grape yield. Based on the curve fitting analysis of various Mg concentrations (with a fixed GABA at 2.5 mM) and yields, the optimal concentration for foliar spraying during the fruit expansion and color change stages was found to be 2.14 mM of Mg. Operationally, it is recommended that grape growers initiate foliar spraying during the middle of the fruit expansion phase (110 days after placing on the trellis), spraying the leaves once every 15 days, and for a total of four applications. In the future, more studies could be carried out for other grape varieties and under different environmental conditions to increase the generalizability of the results.

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