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Research Article

Effects of Silicon on Photosynthetic Characteristics of Maize (*Zea mays* L.) on Alluvial Soil

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The objectives of the study were to determine the effects of silicon on photosynthetic characteristics of maize on alluvial soil, including total chlorophyll contents, photosynthetic rate (P_n), stomatal conductance (g_s), transpiration rate (E), and intercellular CO_2 concentration (C_i) using the method of field experiment, in which there were five levels (0, 45, 90, 150, and 225 $\text{kg}\cdot\text{ha}^{-1}$) of silicon supplying. The results showed that certain doses of silicon fertilizers can be used successfully in increasing the values of total chlorophyll contents, P_n, and g_s and decreasing the values of E and C_i of maize leaves, which meant that photosynthetic efficiency of maize was significantly increased in different growth stages by proper doses of Si application on alluvial soil, and the optimal dose of Si application was 150 $\text{kg}\cdot\text{ha}^{-1}$. Our results indicated that silicon in proper amounts can be beneficial in increasing the photosynthetic ability of maize, which would be helpful for the grain yield and growth of maize.

1. Introduction

Maize (*Zea mays* L.) is the third most important cereal crop in the world after rice and wheat [1]. It is one of the globe's most widely used cereal crops, which is not only an important food crop for human food, but also a basic ingredient of animal feed and raw material for the manufacturing of many industrial products [2].

Fertilizers maintain soil fertility and productivity and therefore make a vital contribution to economic crop production [3]. The application of fertilizers is to supplement the natural supplies of nutrients so that the crop can reach its full growing potential and produce optimum yields [4].

The significance of silicon fertilizers for improving the quality of agricultural products should be mentioned [5]. Silicon (Si) is one of the most abundant elements found in the earth's crust, but is mostly inert and only slightly soluble [6]. Although Si has not been classified as an essential element for higher plants, it has been shown to be beneficial for plant growth [7]. Si has a key role in improving crops' abilities to withstand biotic and abiotic stresses, such as disease and pest resistance, alleviation of heavy metal (Al, Mn, and Fe) toxicities, salinity resistance, resistance to drought stress, and alleviation of freezing stress [8, 9]. The addition of Si in maize can increase water use efficiency by reducing leaf transpiration and water flow rate in the xylem vessel [10]. Si benefits in maize have been related to its effect on the improving of population quality, effective leaf area, and photosynthetic efficiency as well as the delay of leaf senescence [11, 12]. Photosynthesis is a determinant factor for crop growth and development as maximum photosynthesis contributes toward more yield and production, and it is the most basic and critical physiological process directly related to maize yield, especially at late developmental stages [13]. Crop yield potential can be increased by 50% by raising photosynthetic capacity [14].

Table 1: Basic properties of studied soils.

Soil type	Organic matter ($g\cdot kg^{-1}$)	Available nitrogen ($mg\cdot kg^{-1}$)	Available nitrogen ($mg\cdot kg^{-1}$)	Available potassium ($mg\cdot kg^{-1}$)	Available silicon ($mg\cdot kg^{-1}$)	pH
Alluvial soil	22.10	135.32	21.33	92.18	98.30	6.41

Table 2: Effects of Si application on total chlorophyll contents in leaves of maize.

Growth stages	Total chlorophyll contents (mg/g·FW)				
	T1	T2	T3	T4	T5
Big trumpet stage	3.40 ± 0.02^{c}	3.79 ± 0.01^{b}	3.95 ± 0.11^{ab}	4.12 ± 0.05^{a}	4.07 ± 0.15^{a}
Silking stage	7.42 ± 0.11^{c}	7.71 ± 0.04^{b}	7.95 ± 0.02^{b}	8.26 ± 0.02^{a}	8.30 ± 0.08^{a}
Grain filling stage	7.02 ± 0.06^{c}	7.40 ± 0.02^{b}	7.51 ± 0.12^{b}	7.90 ± 0.06^{a}	7.88 ± 0.05^{a}
Milk stage	5.96 ± 0.03^{c}	6.58 ± 0.03^{b}	6.77 ± 0.07^{b}	7.12 ± 0.09^{a}	7.10 ± 0.03^{a}

Means (±SD) labeled with different letters within each column are significantly different ($P < 0.05$) by Duncan's test; $n = 10$.

The purpose of this study was to elucidate the effects of silicon fertilizer, which was conducted in field tests on photosynthetic characteristics and yield of maize on alluvial soil in Northeast China. Optimal application of Si is expected to be an available pathway to increase photosynthetic capacity and efficiency as well as the yield of maize in different kinds of soil.

2. Materials and Methods

2.1. Experimental Site. The field trails were conducted in Agricultural Research Center in Jinsha Village, Huadian City, Jilin Province, China (42°58′ N latitude, 126°44′ E longitude) on an alluvial soil during May to October 2011. This research site lies in midtemperate zone with a continental monsoon climate, a mean annual temperature of about 3.9°C, an average frost-free period of 125 days, the annual sunshine time of about 2, 379 hours, and the annual average precipitation of 748.1 mm with 68% distributed in July-August. The basic properties of the soil from 0 to 20 cm deep are shown in Table 1.

2.2. Experimental Design. The experiment was laid out in a randomized complete block design (RCBD) with three replications having a plot size of 5 m × 10 m. Maize (Zhengdan 958) was sown on May 6 with a density of 65 000 plants·ha^{-1}. The dose of basic fertilization, N, P_2O_5, and K_2O, in all plots was applied, respectively, at the rate of 200 kg·ha^{-1}, 100 kg·ha^{-1}, and 80 kg·ha^{-1}. The experiments consisted of five SiO_2 treatments which included a control named T1 with SiO_2 0 kg·ha^{-1} and four treatments named T2, T3, T4, and T5 with SiO_2 45 kg·ha^{-1}, 90 kg·ha^{-1}, 150 kg·ha^{-1}, and 225 kg·ha^{-1}, respectively. The silicon fertilizer used in the treatments, in the form of a sodium metasilicate ($Na_2SiO_3\cdot H_2O$) with the content of soluble SiO_2 30%, was produced in Yubei Fertilizer Company Limited, Xinxiang City, Henan Province, China. All silicon, phosphate, and potassium fertilizers were applied as basal applications. Nitrogen was applied in two splits (60 percent at basal dressing and 40 percent at elongating stage). This crop was evaluated for its physiological parameters, namely, total chlorophyll contents, net photosynthetic rate (P_n), transpiration rate (E), stomatal conductance (g_s), and intercellular CO_2 concentration (C_i). The observations were recorded at four growth stages, big trumpet stage (or the 12-leaf stage), silking stage, grain filling stage, and milk stage.

2.3. Measurement of Total Chlorophyll Contents. Chlorophyll was extracted using ethanol-acetone solution (v/v 1 : 1) [15, 16]. A UV/VIS spectrophotometer was used to determine the absorbance of chlorophyll a and chlorophyll b in the extracts at 663 nm and 645 nm, respectively. Total chlorophyll content was calculated by using the following formula: chlorophyll a + b ($mg\cdot g^{-1}\cdot FW$) = $[20.2 \times (A_{645}) - 8.02 \times (A_{663})] \times 0.5$.

2.4. Measurement of Gas Exchange Parameters. At the four growth stages, the gas exchange parameters, P_n, E, g_s, and C_i, of the top second fully expanded leaf were measured using a portable open flow gas exchange system LI-6400 (LI-COR Inc., USA) between 9:00 am and 11:00 am in the field. Photosynthetically active radiation was 2000 $\mu mol\cdot m^{-2}\cdot s^{-1}$, CO_2 concentration was 350 $\mu mol\cdot mol^{-1}$, and leaf temperature was 25°C [15, 17].

2.5. Statistical Analysis. Data from these experiments were analyzed through one-way analysis of variance (ANOVA) using SPSS Version 17.0 for Windows and means were compared by Duncan's test at 0.05 significance level.

3. Results

3.1. Total Chlorophyll Contents. Total chlorophyll contents were measured from big trumpet stage to milk stage (Table 2). Similar tendency of total chlorophyll contents was found for all of the 5 treatments; that is, the total chlorophyll contents increased first from big trumpet stage to silking stage and reached the peak values at silking stage, after which total chlorophyll contents decreased with maize growing. Total chlorophyll contents under Si application treatments in the same stage were all remarkably higher than those of the

Table 3: Effects of Si application on net photosynthetic rate (P_n) in leaves of maize.

Growth stages	Photosynthetic rate (P_n) (μmo1·m^{-2}·s^{-1})				
	T1	T2	T3	T4	T5
Big trumpet stage	23.21 ± 0.61^{c}	26.33 ± 0.79^{b}	27.96 ± 0.85^{b}	29.16 ± 0.55^{a}	29.37 ± 0.37^{a}
Silking stage	38.36 ± 0.71^{d}	42.15 ± 0.92^{c}	45.06 ± 0.80^{b}	47.83 ± 0.77^{a}	47.92 ± 0.56^{a}
Grain filling stage	28.13 ± 0.52^{d}	31.79 ± 0.36^{c}	34.65 ± 0.43^{b}	38.68 ± 0.51^{a}	38.56 ± 0.62^{a}
Milk stage	11.36 ± 0.39^{d}	14.82 ± 0.26^{c}	19.63 ± 0.41^{b}	21.60 ± 0.32^{a}	21.26 ± 0.28^{a}

Means (±SD) labeled with different letters within each column are significantly different ($P < 0.05$) by Duncan's test; $n = 10$.

Table 4: Effects of Si application on transpiration rate (E) in leaves of maize.

Growth stages	Transpiration rate (E) (mmol·m^{-2}·s^{-1})				
	T1	T2	T3	T4	T5
Big trumpet stage	7.73 ± 0.06^{a}	7.65 ± 0.09^{a}	7.16 ± 0.03^{b}	6.93 ± 0.05^{c}	6.85 ± 0.08^{c}
Silking stage	12.81 ± 0.12^{a}	12.95 ± 0.15^{a}	11.83 ± 0.13^{b}	9.86 ± 0.07^{c}	9.91 ± 0.06^{c}
Grain filling stage	7.66 ± 0.10^{a}	7.47 ± 0.07^{a}	6.81 ± 0.09^{b}	5.95 ± 0.08^{c}	5.25 ± 0.06^{d}
Milk stage	3.30 ± 0.05^{a}	3.35 ± 0.06^{a}	3.02 ± 0.04^{b}	2.97 ± 0.03^{b}	2.95 ± 0.05^{c}

Means (±SD) labeled with different letters within each column are significantly different ($P < 0.05$) by Duncan's test; $n = 10$.

control (without Si application). In studying of all the growth stages, the total chlorophyll contents were also significantly increased by increasing Si application from the dose of 45 kg·ha^{-1} to the dose of 150 kg·ha^{-1} Si (T2, T3, and T4) and there were no significant differences between the treatments of T4 and T5, which were at the doses of 150 kg·ha^{-1} and 225 kg·ha^{-1} Si, respectively.

3.2. Gas Exchange Parameters. It was observed that changes in gas exchange parameters, net photosynthetic rate (P_n), transpiration rate (E), and stomatal conductance (g_s) (Tables 3, 4, and 5) showed a similar pattern to that observed in total chlorophyll content (Table 2), that is the values measured of these parameters during the four studied growth stages increased first from big trumpet stage and reached the peak values at silking stage, after which those values decreased gradually as maize grew.

3.3. Net Photosynthetic Rate (P_n). As shown in Table 2, data on net photosynthetic rate (P_n) differed significantly among different levels of Si fertilizer. In each of the 5 treatments of all studied growth stages, the maximum and minimum values of P_n were observed, respectively, at silking stage and milk stage. P_n under Si application treatments in the same growth stage increased with concurrent increase from the dose of 45 kg·ha^{-1} to the dose of 150 kg·ha^{-1} Si (T2, T3, and T4), and there were no significant differences between the treatments of T4 (150 kg·ha^{-1} Si) and T5 (225 kg·ha^{-1} Si).

3.4. Transpiration Rate (E). For the parameter transpiration rate (E) (Table 4) studied during each of the four growth stages, the highest values of E were observed in treatments T1 (without Si application) and T2 (45 kg·ha^{-1} Si), between which there were no significant differences; in each growth stage the values of E under treatments T3, T4, and T5 were significantly lower than those under T1 and T2. *In each of the growth stages, the values of E decreased with the increasing dose of Si fertilizer.* In observing each growth stage, comparing the values of E under treatments T3, T4, and T5 with those under treatment T1, the results showed that during big trumpet stage, the former decreased by 7.3%, 11.3%, and 8.0%, respectively, more than that of the latter; during silking stage, the former decreased by 7.6%, 23.0%, and 22.6%, respectively, more than that of the latter; during grain filling stage, the former decreased by 11.0%, 22.3%, and 31.4%, respectively, more than that of the latter; during milk stage, the former decreased by 8.4%, 10.0%, and 10.6% more than that of the latter.

3.5. Stomatal Conductance (g_s). During the four stages from big trumpet stage to milk stage, Si application at the levels of 45 kg·ha^{-1} (T2), 90 kg·ha^{-1} (T3), 150 kg·ha^{-1} (T4), and 225 kg·ha^{-1} (T5) resulted in significant ($P < 0.05$) increases in the values of stomatal conductance (g_s) of maize as compared to that of the control group (T1), the effects among the five levels of Si application on the values of g_s followed the sequence T5 > T4 > T3 > T2 > T1 (Table 5). An increased Si supply from the dose of 45 kg·ha^{-1} to the dose of 225 kg·ha^{-1} increased the values of g_s in maize leaves significantly. The highest values were at treatment T5. There were no significant differences between treatments T2 and T3 as well as T4 and T5.

3.6. Intercellular CO_2 *Concentration* (C_i). During the four studied growth stages, changes in intercellular CO_2 concentration (C_i) (Table 6) showed a similar pattern among the five Si application treatments T1, T2, T3, T4, and T5, that is the values of C_i decreased first from big trumpet stage to grain filling stage, at which the lowest values of C_i were observed and then increased slowly at milk stage. In each growth stage, increased Si supply under the treatments of T3, T4, and T5 always significantly ($P < 0.05$) decreased the values of C_i compared with those of T1 and T2; the values of

TABLE 5: Effects of silicon on stomatal conductance (g_s) in leaves of maize.

Growth stages	Stomatal conductance (g_s) (mol·m^{-2}·s^{-1})				
	T1	T2	T3	T4	T5
Big trumpet stage	0.43 ± 0.03^c	0.49 ± 0.02^b	0.50 ± 0.06^b	0.59 ± 0.02^a	0.61 ± 0.03^a
Silking stage	0.72 ± 0.05^c	0.77 ± 0.03^b	0.79 ± 0.02^b	0.88 ± 0.03^a	0.89 ± 0.01^a
Grain filling stage	0.55 ± 0.02^c	0.63 ± 0.02^b	0.66 ± 0.05^b	0.70 ± 0.04^a	0.72 ± 0.02^a
Milk stage	0.22 ± 0.03^c	0.31 ± 0.01^b	0.33 ± 0.03^{ab}	0.35 ± 0.01^a	0.36 ± 0.03^a

Means (±SD) labeled with different letters within each column are significantly different ($P < 0.05$) by Duncan's test; $n = 10$.

TABLE 6: Effects of silicon on intercellular CO_2 concentration (C_i) in leaves of maize.

Growth stages	Intercellular CO_2 concentration (C_i) (μmol·mol^{-1})				
	T1	T2	T3	T4	T5
Big trumpet stage	180.16 ± 1.13^a	174.77 ± 2.29^{ab}	169.81 ± 1.42^b	156.59 ± 1.67^c	155.62 ± 1.96^c
Silking stage	154.40 ± 2.31^a	153.23 ± 2.25^a	143.916 ± 1.36^b	132.50 ± 2.12^c	133.62 ± 2.03^c
Grain filling stage	143.73 ± 1.81^a	140.29 ± 1.38^a	133.65 ± 2.27^b	123.70 ± 1.58^c	122.52 ± 2.06^c
Milk stage	145.30 ± 1.16^a	143.96 ± 2.00^a	137.58 ± 1.06^b	126.66 ± 1.79^c	125.73 ± 1.18^c

Means (±SD) labeled with different letters within each column are significantly different ($P < 0.05$) by Duncan's test; $n = 10$.

C_i of each growth stage significantly decreased with the dose of Si increasing from 90 kg·ha^{-1}, but there were no significant differences between the doses of 150 kg·ha^{-1} and 225 kg·ha^{-1}.

4. Discussion

Our results showed that in leaves of maize on alluvial soil, the values of chlorophyll contents, P_n, and g_s were significantly increased and those of E and C_i decreased with Si supplied; similar results were reported by a number of studies in different kinds of crops [17–20]. Silicon has a number of functions such as stimulation of photosynthesis, enhancement of tissue strength, and reduction of plant transpiration rate [21].

Our researches showed that in each growth stage, chlorophyll contents and P_n under treatments with Si application were significantly increased compared with those under control (without Si application). Chlorophylls play roles not only in the capacity but also in the efficiency of plants' photosynthesis. The improvement of maize photosynthesis might be the result of increased total chlorophyll contents and P_n by optimum Si application on alluvial soil. These results are consistent with the finding of Zeng et al. [22] and Cao et al. [23] who, respectively, found that leaf senescence of sugarcane (*Saccharum officinarum* L.) during which chloroplasts together with chlorophylls are breaking down could be delayed with Si application, by which photosynthetic rate (P_n) and efficiency can be improved; the crop yield can by greatly improved by optimum doses of Si application, which is due to increasing chlorophyll contents. Effects of silicon deposited in leaves on improving photosynthetic potential and efficiency by opening angle of leaves, keeping the leaf erect, and decreasing self-shading have been reported in rice (*Oryza sativa* L.), barely (*Hordeum vulgare* L.), wheat (*Triticum aestivum* L.), and sugarcane (*Saccharum officinarum* L.) [24]. Photosynthetic capacities of crops' applied Si are improved by the enlarged size of chloroplasts and the increased number of grana in leaves [19].

According to our research, during big trumpet stage to milk stage, the values of transpiration rate (E) under the Si doses of 90 kg·ha^{-1}, 150 kg·ha^{-1}, and 225 kg·ha^{-1} were significantly lower than those of the control with SiO_2 0 kg·ha^{-1} or low-level Si application with SiO_2 45 kg·ha^{-1}. It means that transpiration rate (E) of maize can be decreased and net photosynthetic rate (P_n) can be increase by Si application on alluvial soil. It is important to use optimum levels of Si fertilizer to increase water use efficiency for maize drought resistance in dry areas. Similar reports by Ren et al. [3] showed that the reduced water loss in maize with Si application was due to the changed morphological structures of leaf epidermal cells. Ourresults can be explained from the point of view of anatomic structure of leaves by Si application; Lewin and Reimann [25] reported a combination of silica with cellulose in the epidermal cells of leaf blade, above this a layer of silica and then on the outside a very thin cuticle, which attributed great significance to this double layer (i.e., a cuticle layer plus a layer of silica) in limiting unnecessary water loss through the epidermis. According to the former researches [11], the role of Si in decreasing transpiration rate largely attributed to the reduction in transpiration rate from stomata rather than cuticula; Agarie et al. [26] found that Si could influence the stomata opening.

Increases of stomatal conductance (g_s) were found from big trumpet stage to milk stage, and there were significant differences between the control (Si dose of 0 kg·ha^{-1}) and the treatments with Si doses of 45 kg·ha^{-1}, 90 kg·ha^{-1}, 150 kg·ha^{-1}, and 225 kg·ha^{-1}, which suggested g_s of maize leaves can be increased by Si application. Similar reports on strawberry (*Fragaria chiloensis* (L.) Mill.) [17], tomato (*Lycopersicon esculentum* Mill.) [23], rice (*Oryza sativa* L.) [20, 27], and wheat (*Triticum aestivum* L.) [28, 29] showed that g_s can be increased by Si fertilizer. Increases in g_s, which regulates gas exchange (CO_2 and water), can allow plants under well-watered growth conditions to increase their CO_2 uptake and subsequently enhance photosynthesis [30]. Under normal water conditions, the values of g_s increase together with the increasing of photosynthetic rate, by which crops regulate stomatal conductance to reduce water loss [31, 32].

In different growth stages, a similar pattern of the five Si treatments showed that the maximum values of C_i were observed at big trumpet stage, from which C_i decreased gradually and got minimum values at grain filling stage, after which the values of C_i increased slightly. That may be the result of leaf senescence of maize in milk stage, during which the activities of photosynthetic enzymes in photosystems gradually decrease and the values of C_i begin to increase [33]. From grand growth stage to milk stage, the values of C_i by Si treatments 90 kg·ha^{-1}, 150 kg·ha^{-1}, and 225 kg·ha^{-1} were significantly lower than those by the control with a Si dose of 0 kg·ha^{-1} and low Si treatment with the a dose of 45 kg·ha^{-1}, which explains that photosynthetic efficiency of leaves was increased by exogenous silicon [34], which inhibited the activities of photosynthetic enzymes in mesophyll cells from decreasing [23].

5. Conclusion

Silicon fertilizers can be used successfully in maize on alluvial soil. The field study demonstrates that Si application was closely related to the values of these parameters of total chlorophyll contents, photosynthetic rate (P_n), stomatal conductance (g_s), transpiration rate (E), and intercellular CO_2 concentration (C_i) of maize plants. Increased Si supply increased the values of total chlorophyll contents, photosynthetic rate (P_n), and stomatal conductance (g_s) of maize leaves, while increased Si application decreased thevalues of transpiration rate (E) and intercellular CO_2 concentration (C_i) of maize leaves. In this research the results showed that the optimal dose of Si application was 150 kg·ha^{-1}, under which photosynthetic efficiency and ability of maize leaves were greatly increased in different growth stages. In conclusion, our results indicated that maize photosynthetic efficiency and ability can be significantly increased by proper doses of Si application which would greatly improve the yield of maize. Thus, silicon in proper amounts can be beneficial in increasing grain yield and in growth of cereal crops [35].

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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