EFFECT OF SILICON ON CROP YIELD, AND NITROGEN USE EFFICIENCY APPLIED UNDER STRAW RETURN TREATMENTS

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Abstract. Nitrogen (N) is an essential element for crop growth and for improving crop yield. A two-year field experiment was carried out in China to test the effects of silicate (Si) fertilizer with straw return on N use efficiency (NUE) and yield of spring maize. Four treatments were arranged in a randomized block design: SI+ST (straw return + 45 kg ha^{-1} Si), SI (no straw return + 45 kg ha^{-1} Si), ST (straw return + no Si) and C (no straw return + no Si). The results showed that the accumulation of dry matter and grain yield under SI were 6.5% and 8.8% higher, respectively than those under the C. The N uptake under SI increased by 15.6% compared with that under the C treatment. The N uptake of SI+ST increased by 7.6% compared to SI. The SI+ST resulted in a significant increase in the AEN, REN, and PFPN compared with SI. The above results show that the use of Si fertilizer combined with straw return significantly provides better N for maize growing stages and is recommended as an alternative method to simultaneously increase crop yield and NUE while reducing the use of chemical fertilizer to the environment.
Keywords: *crop residues, Si-based fertilizer, spring maize, N utilization, grain yield*

Introduction

Nitrogen (N) is an essential nutrient for maize growth and is considered to be the main controlling factor for plant productivity after water deficiency (Lea and Azevedo, 2006). The high yield of the crop is associated with the application of a large amount of N fertilizers (Patel et al., 2017). The N use efficiency (NUE) of plants is the primary index used to determine nutrient uptake (Yang et al., 2003). It measures the ability of crops to accumulate and utilize nutrients for maximum yields (González-Fontes et al., 2017). NUE depends on the plant’s ability to take up nutrients efficiently from the soil but also depends on internal transport, storage, and remobilization (Prieto et al., 2017). Thus, it involves three major processes in plants: uptake, assimilation, and utilization of nutrients (Baligar et al., 2001; Reich et al., 2014). Cereal NUE in china was approximately 41%, and they're still the applying of excess N fertilizer, which has consequently resulted in low NUE (Omara et al., 2019). Many measures have been recommended to enhance plant NUE including proper management of rhizosphere processes (Zhu et al., 2010), the use endophytic bacteria (Prieto et al., 2017), conservation agriculture (Jat et al., 2012), through alteration of amino acid transport processes (Perchlik and Tegeder, 2017) and the use of split application of reduced nitrogen (Du et al., 2019b). Therefore, the best N fertilizer management practice has to be adopted to improve NUE in crops. Management of N is a complex task, and several approaches individually and in combination, have been engaged to manage its effectiveness (Sharma and Bali, 2018).

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Silicon (Si) is the most abundant element on the earth's surface, which has proved to have many beneficial effects for crops (Deshmukh et al., 2017). Si has been reported to have a significant effect on yield and modify growth in crops (Luz et al., 2008). Previous research has discovered that Si can stimulate various plants to take up more macronutrients and micronutrients (Ca, P, S, Mn, Zn, Cu, Cl, Fe) from the soil (Islam and Saha, 1969; Owino-Gerroh and Gascho, 2005; Greger et al., 2018). According to previous studies (Singh et al., 2006; Jugal and Ramani, 2017; Patel et al., 2017), the application of Si has a synergistic relationship with N in rice. Recent studies have shown that Silicon (Si) also influenced the nutrient uptake and accumulation in non-stressed crops (Greger et al., 2018). Si enhances NUE, P availability, and carbon turnover in wheat crops (Neu et al., 2017). Si application influenced the availability of N uptake, which enhances the increase of biomass and prevents N starvation in plants (Haddad et al., 2018).

Crop straw is rich in plant nutrients such as nitrogen, phosphorus, and potassium, and many trace elements (Gao et al., 2009). Wang et al. (2019) reported that straw return remarkably increased N uptake and grain yield in maize-wheat rotation. The combination of organic and inorganic fertilizers enhanced the N uptake, the N use, and recovery from the soil in rice (Moe et al., 2017). Incorporation of straw into soil improved the NUE and carbon inputs (Eagle et al., 2001). Apart from the increased NUE, the use of wheat straw significantly increased the nitrogen agronomic efficiency (AEN), the nitrogen recovery efficiency (REN), the nitrogen physiological efficiency (PEN), and the nitrogen partial factor productivity (PFPN) (Hu and Zhang, 2017). Appropriate management of organic matter ensures conservation and provisions nutrients in a prolonged period in crop production (Watson et al., 2002).

The enhancement of NUE in crops has been shown mainly by the application of Si or straw individually in previous researches. There is currently no research on Si combined with straw return on NUE in crops. We hypothesized that though apply Si could stimulate plants to take up more N from the soil, however, due to the fixation of silicon fertilizer in the soil, its effect only lasts for a short time. The straw can not only increase the nutrients in the soil but can also improve Si availability at the late stages of growth. Thus, meet crop needs and enhance plant growth and development in later stages and sustainably enhance grain yield. The main objective of the study was to investigate the effect of silicate fertilizer with straw on N uptake, remobilization, NUE, and yield in spring maize. The findings of the study could add to the development strategies that improve NUE and sustainably to enhance crop yield.

Materials and Methods

Experimental design and crop management

Two field trials were established at Dong Fang Hong village (124 °31'E, 43 °55'), Nong'an County, Changchun city, Jilin Province in China, in the 2017 and 2018 growing seasons. The soil was Chernozem (soil classification is based on the Canadian system of soil classification) (Haynes, 1998) containing 27.96 and 25 g kg^{-1}, 107.31 and 109.2 mg kg^{-1} alkaline nitrogen (N), 50.73 and 33.9 mg kg^{-1} available phosphorus (P), 163.59 and 114.1 mg kg^{-1} available potassium (K), 350.19 and 357 mg kg^{-1} available silicon (Si), 8.02 and 7.7 soil pH before maize planting at a soil depth 0-20 cm in 2017 and 2018, respectively. Spring maize is the maize grown during the spring season and are sensitive to climate change.

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The experiments had a two-way factorial design in which 12000 kg ha^{-1} (J) of straw was returned to the field in one area, and the other area had no straw returned to the field (W). The Si treatments included the S0 treatment (0 kg ha^{-1}, no Si fertilizer) and the S3 treatment (45 kg ha^{-1} of Si fertilizer). There were four treatments: C (no Si fertilizer + no straw), SI (Si fertilizer + no straw), ST (no Si fertilizer + straw) and SI+ST (Si fertilizer + straw). The treatments were arranged in a randomized block design (RBD) with three replications. Sodium silicate (Na_2SiO_3) was used as Si fertilizer. The area of each plot was 35 m^2. The maize variety Fumin 985 (produced by Jilin Fumin Seed Leaf Co., Ltd) was planted on May 7, 2017, and May 10, 2018, and then harvested on September 28, 2017, and October 2, 2018, respectively. The planting density was 65000 plants ha^{-1}. Macronutrients (nitrogen, phosphorus, and potassium) were applied in the experimental plots. The rate of N application was 240 kg ha^{-1} in each treatment, in which the base fertilizer accounted for 40% of the total N application rate, the topdressing fertilizer at the jointing stage accounted for 30% of the total N application rate, and the topdressing fertilizer at the heading stage accounted for 30% of the total N application rate. All plots were treated with phosphorus pentoxide (P_2O_5, 100 kg ha^{-1}) and potassium oxide (K_2O, 100 kg ha^{-1}), which were applied once as the base fertilizers. The remainder of the management was based on the high standard of field production.

Plant sampling and tissue nutrient analysis

Three samples of fresh plants were collected from each plot at growth stages V6 (six leaves), V12 (twelve leaves), VT (tasseling), R2 (blister aging), R3 (milking) and R6 (maturity) (June 29, July 18, July 27, August 22, September 7, and September 27 in 2017 and July 15, July 24, August 2, August 23, September 11, and September 28 in 2018, respectively). Plant samples were divided into four components: stem (including the stem, leaf sheath, and bract leaf), leaf, cob, and grain. Plant samples were heated at a constant temperature in a blast oven at 105 °C for 30 min and dried to a uniform weight at 80 °C. Each plant piece was weighed to obtain its dry weight (DW). The total N content of the different plant organs was extracted by the Kjeldahl method.

Grain yield and yield components

At maize maturity, the yield was measured in each experimental plot with a representative area of 10 m^2, and ten ears were selected according to the weight mean method to measure the grain number per ear and the 1000-grain weight. The economic yield was calculated by the air-dry weight (14% water content) of 10 grains in each plot.

Calculations

(Mi et al., 2003; Chen et al., 2014; Agegnehu et al., 2016; Du et al., 2016, 2019a; Deng et al., 2018).

Nitrogen change and N remobilization

To model the N uptake pattern, a logistic model was used to describe the progress of the plant N uptake as follows:

$$N = \frac{N_{\max}}{1 + ae^{bt}} \qquad \text{(Eq.1)}$$

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$$t_1 = -\frac{1}{b}\ln\frac{2+\sqrt{3}}{a} \qquad \text{(Eq.2)}$$

$$t_2 = -\frac{1}{b}\ln\frac{2-\sqrt{3}}{a} \qquad \text{(Eq.3)}$$

where is the N uptake in maize, N_{max} (kg ha^{-1}) is the asymptotic maximum N uptake by maize, and a and b are the constants to be determined. The time of the N uptake rate acceleration is t_1, the time of the N uptake rate deceleration is t_2, t_2-t_1 is the fast uptake duration of maize N.

N accumulation amount in the plant,

NAA (kg ha^{-1}) = Plant dry weight (kg ha^{-1}) × Plant N content (%) (Eq.4)

N remobilization amount (kg ha^{-1}) = maximum N content during the growth period - N content at maturity (Eq.5)

N remobilization efficiency (%) = (maximum Mg content during the growth period - Mg content at maturity) / maximum Mg content during the growth period × 100 (Eq.6)

Apparent contribution to grain by N remobilization (%) = (maximum N content during the growth period – N content at maturity)/grain N content at maturity × 100 (Eq.7)

Nitrogen use efficiency

The AEN, REN, PEN, and PFPN were computed using the below formulas:

$$PFPN = \frac{YT}{FN} \qquad \text{(Eq.8)}$$

$$AEN = \frac{AY}{NA} \qquad \text{(Eq.9)}$$

$$REN = \frac{ANU}{NA} \qquad \text{(Eq.10)}$$

$$PEN = \frac{AY}{ANU} \qquad \text{(Eq.11)}$$

where, AEN is the increased maize grain yield (ΔY) over zero- N plots per unit area of fertilizer N applied (NA). REN is the increased total N uptake over zero-N plots (ΔNU). PFPN is the maize total grain yield (YT) per unit area of fertilizer N applied (FN) Kg of N per ha applied. PEN is the increased maize grain yield per unit area (ΔY) of increased N uptake over zero- N plots (ΔNU).

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Statistical data analysis

Total N accumulation (kg ha^{-1}), remobilization amount (kg ha^{-1}), remobilization efficiency (%), apparent transfer to the grain (%) and total dry matter accumulation (kg ha^{-1}) at different growth stages and the grain yield and yield components were analyzed using SPSS Statistics 25.0 (SPSS, Inc., Chicago, IL, USA). Differences in mean C, SI, ST, and SI+ST treatments were tested for statistical significance by analysis of variance (ANOVA). One-way ANOVA was used to test for differences in mean C, SI, ST, and SI+ST during the maize growth. Two-way ANOVA was used to test for the effects of Si fertilizer, straw return, and their interaction of mean C, SI, ST, and SI+ST. In case of significant differences among the means, DUNCAN significant differences at $P = 0.05$ test was used. Figures were created in Origin Pro 8. Means and standard errors (S.E) from the statistical analysis were brought into Origin Pro 8, and diagrams were created using the line+ symbol and column graph tools.

Results

Maize grain yield components

As shown in *Table 1*, the yield of Si-fertilized treatments was higher than that without silicate fertilizer. Compared with the C with an average yield of 11124 kg ha^{-1}, the corn yield of SI treatment was higher, with an average yield of 11671 kg ha^{-1} in two years (*Table 1*). In both years, significant differences in grain number and 1000-grain weight observed between Si-fertilized treatments and treatments without Si fertilizer. The two-year average yield of the SI+ST treatment (11829 kg ha^{-1}) was higher than that of the SI treatment (11671 kg ha^{-1}) (*Table 1*). Averaged over two years, the crop productivity of SI increased by 4.8% on average compared with that of C (*Table 1*).

Table 1. *Showing variance analysis of grain number (per ear), 1000-grain weight (g), and yield (kg ha^{-1}), and increased productivity of maize in two consecutive years of 2017-2018*

Year	Treatment	Grain Number (per Ear)	1000-Grain Weight (g)	Yield (kg ha^{-1})	Increased Productivity (%)
2017	C	597±4c	300±11c	11196±359c	-
	SI	597±14c	330±7a	11685±221a	4.4
	ST	635±5b	314±2b	11345±11b	1.3
	SI+ST	693±33a	330±4a	11881±107a	6.1
2018	C	329±6b	527±3c	11052±155c	-
	SI	336±4ab	550±8a	11657±30a	5.3
	ST	333±21ab	542±62b	11067±24b	0.1
	SI+ST	346±4a	556±2a	11777±134a	6.4

Total dry matter accumulation in maize

Dry matter accumulation was affected by Si and straw applications over the two experimental years (*Fig. 1*). All the treatments showed a similar trend of total biomass accumulation in maize. At the V6 stage, the level of dry matter was low, and there were no differences among treatments; then, the biomass increased continuously with the age of the maize plant until maturity, and the differences between different treatments

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gradually increased. At harvest time, the dry matter accumulation under the SI treatment increased by 6.1% on average compared to that under the C treatment. The total dry matter under the SI+ST treatment increased by 2.9% on average compared with that under the SI treatment. In both years, there was a significant difference between the straw application treatments and those with no straw.

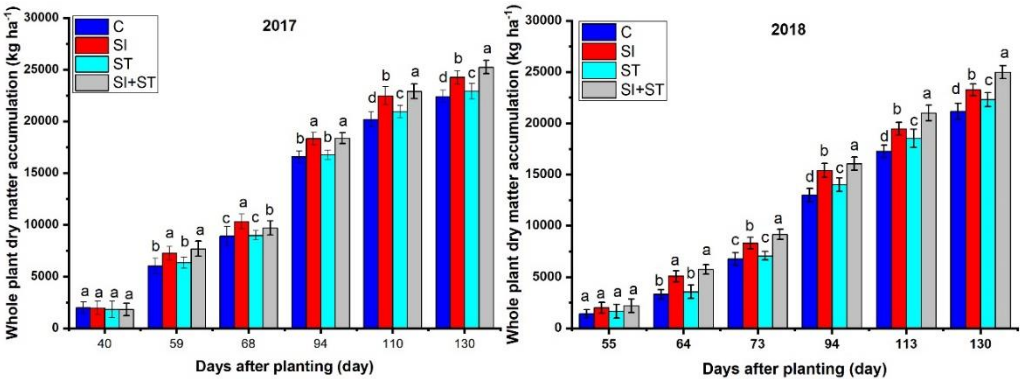

Figure 1. *The seasonal total dry matter accumulation of Si evaluated for two years, 2017 and 2018. Values are means with standard deviations shown by vertical bars (n=4). Bars with a different lowercase letter (s) in the same planting date indicate significant differences at P < 0.05 among the treatments*

Total N uptake and total N uptake rate in spring maize

N uptake in maize increased from the V6 stage to physiological maturity, and there were significant differences among the Si and straw treatments. The N uptake of the SI treatment was 15.9% higher than that of the C treatment at the maturity stage. The effect of the straw application on maize N uptake was significant (*Fig. 2*). The N uptake under the SI+ST treatment increased by 7.7% compared to that under SI treatment. During the period of the fast N uptake stage, the uptake rate under the SI treatment had a mean rate of 10.4% higher than that under the C treatment in both years. In comparison with the SI treatment, the SI+ST treatment showed a noticeable increase in N uptake by the crop. The uptake rate of SI+ST treatment had a mean rate of 3.8% higher than that of SI treatment, averaged over two years.

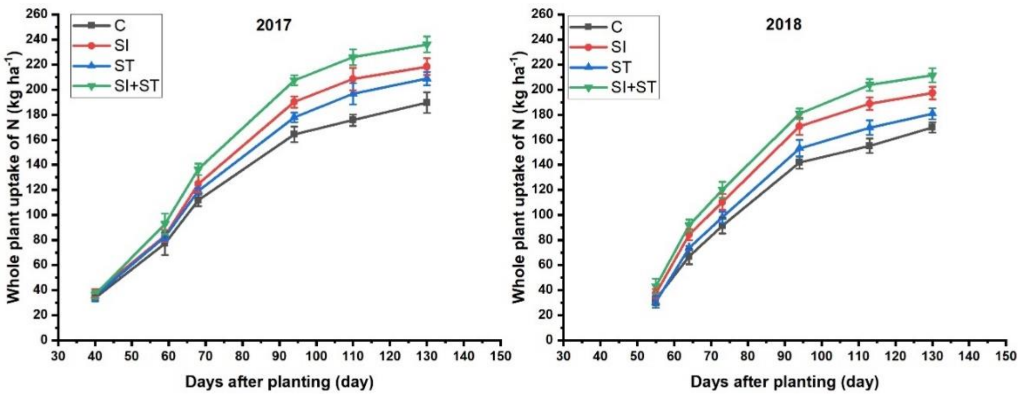

Figure 2. *The response of maize total plant N uptake for two years, 2017 and 2018. Each data point is the mean ± S.E. of three replications*

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N remobilization in spring maize

The result showed that the remobilization of nitrogen in leaves and stems in two years under all treatments manifested the same tendency (SI+ST >SI>ST>C) (*Table 2*). Averaged over two years, the remobilization amount, the remobilization efficiency, and contribution to the grain under the SI treatment increased by 21%,4%, and 6.8%, respectively, compared to the conventional practice application (C). The remobilization amount, the remobilization efficiency, and the contribution to the grain under the plots treated with straw increased by 7.9%, 1.1%, and 3.6%, respectively, compared to that with no straw when averaged over two years.

Table 2. *Analysis of variance of the vegetative Si remobilization amount (mg kg^{-1}), remobilization efficiency (%) and contribution to the grain (%) in two successive years (2017-2018)*

		N remobilization Amount (kg ha^{-1})			**N remobilization efficiency (%)**			**Apparent contribution to grain N by N remobilization (%)**		
		leaves	stem	total	leaves	stem	total	leaves	stem	total
2017	C	31.7± 0.53b	15.5± 0.95b	47.2± 0.66c	41.2± 1.29a	50.6± 0.66b	44.4± 1.62a	29.6± 0.15c	19.3± 0.21d	48.9± 0.41d
	SI	40.3± 0.43b	17.9± 0.27ab	58.2± 0.39b	42.6± 1.28b	52.0± 1.67c	45.7± 1.48c	33.6± 0.04b	19.8± 0.25b	53.4± 0.12b
	ST	36.4± 0.24b	14.00± 0.17c	50.4± 0.24d	42.0± 1.54a	47.8± 1.49a	43.9± 1.18b	31.9± 0.11b	18.5± 0.07c	50.4± 0.10c
	SI+ST	44.1± 0.03a	17.4± 0.45a	61.5± 0.21a	43.1± 0.41b	52.4± 1.19b	46.1± 1.17c	34.6± 0.20a	20.3± 0.34a	54.9± 0.23a
2018	C	26.8± 0.76c	18.3± 1.91c	45.1± 1.35c	39.2± 1.31a	47.8± 0.97a	42.3± 2.51a	28.2± 0.19c	19.2± 0.23c	47.4± 0.49c
	SI	32.8± 0.96ab	22.8± 1.87ab	55.6± 1.87a	40.8± 0.83c	51.3± 0.22b	44.5± 1.41c	29.2± 0.05b	20.3± 0.22b	49.5± 0.22b
	ST	30.0± 0.90b	20.8± 1.39bc	50.8± 1.82b	38.7± 0.40b	51.1± 0.25b	43.0± 2.57b	28.8± 0.04b	20.0± 0.25b	48.8± 0.10b
	SI+ST	35.6± 4.33a	25.7± 1.95a	61.3± 0.68a	41.0± 1.51a	52.1± 0.23c	45.1± 3.28d	30.0± 0.21a	21.7± 0.97a	51.7± 0.29a
Anova										
F		NS	**	*	**	**	**	**	**	**
S		**	NS	**	NS	**	**	**	*	**
FS		NS	NS	NS	*	NS	NS	**	**	**
FSY		*	*	NS	NS	NS	NS	**	**	**

Note: F: fertilizer, S: straw, F × S: fertilizer with straw, FSY: fertilizer × straw × year. NS, not significant (p-value>0.05); *, significant at (p-value<0.05); **, significant at (p-value<0.01)

N use efficiency (NUE) in spring maize

The data indicated that the AEN, REN, and PFPN were significantly increased with the Si fertilizer application (*Table 3*). Compared to the C treatment, the SI treatment resulted in increases in AEN, REN, and PFPN of 13.6%, 44.9%, and 4.9%, respectively, averaged over two years. The PEN under SI treatment decreased by 26.7% compared to that of the C treatment, averaged over two years. The AEN, REN, and PFPN of the SI+ST treatment increased by 3.6%, 17.6%, and 1.3%, respectively, compared to that under SI treatment. the PEN decreased under the SI+ST treatment by 13.5% when averaged in two years.

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Table 3. *Variance analysis of the N use efficiencies (Eq.8,9,10 and 11); - agronomic use efficiency (mg kg^{-1}), recovery use efficiency (%), and physiological use efficiency (kg ha^{-1}), and partial factor productivity of N (PFPN) in two consecutive years of 2017-2018*

	Treatments	Agronomic N Use Efficiency (AEN) kg kg^{-1}	Recovery N Use Efficiency (REN) %	Physiological N Use Efficiency (PEN) kg kg^{-1}	N partial factor productivity (PFPN) kg kg^{-1}
2017	C	16.03±0.09c	26.99±0.25d	59.39±0.15a	46.65±0.37d
	SI	18.07±0.14ab	38.89±0.68b	46.46±0.26b	48.69±0.33b
	ST	16.65±0.04b	34.94±0.29c	47.65±014b	47.27±0.17c
	SI+ST	18.88±0.37a	46.29±0.19a	40.78±0.02c	49.50±1.29a
2018	C	15.78±0.07c	24.95±0.16d	63.23±0.03a	46.05±0.08c
	SI	18.30±0.18b	36.36±0.12b	50.32±0.22c	48.57±0.22b
	ST	15.85±0.23c	29.52±0.21c	53.68±0.17b	46.11±0.03c
	SI+ST	18.80±0.37a	42.28±0.02a	44.46±0.32d	49.07±0.004a
Anova					
F		**	**	**	**
S		*	**	**	**
F S		NS	NS	**	*
FSY		NS	*	**	NS

F: fertilizer, S: straw, F × S: fertilizer with straw, FSY: fertilizer × straw × year. NS, not significant (p-value>0.05); *, significant at (p-value<0.05); **, significant at (p-value<0.01)

Discussion

Maize biomass yield, grain yield, and increased productivity

Silicon (Si) is closely related to plant growth and yield owing to strengthen the physiological attributes of the maize (Kaya et al., 2006; Amin et al., 2016). Si has proved to enhance the photosynthesis process, improves the absorption of nutrients, and increases grain yield in maize (Xu et al., 2016). The results present in *Table 1* illustrate that the maize grain and dry matter significantly influenced by Si application. The substantially higher grain yield (11685 kg ha^{-1} and 11657 kg ha^{-1}) in 2017 and 2018 were recorded due to the basal application of Si, while the lower grain (11196 kg ha^{-1} and 11052 kg ha^{-1}) were registered under the conventional practice. The treatment SI gave a 6.5% higher dry matter over C (*Fig. 1*). The result was consistent of the report by Xu et al. (2016), who found that the application of Si improved maize grain yield and dry matter accumulation.

Huang et al. (2010) mentioned the application of organic fertilizer combined with inorganic fertilizer is a good fertilization practice for modifying soil quality and attaining optimum yield. Many reports have shown that straw return provides nutrients, and it's associated with improved biomass yield and grain yield (Zhang et al., 2009; Xu et al., 2010; Wang et al., 2018). The findings from this trial demonstrate that the addition of Si fertilizer and straw increases grain yield and dry matter of maize in two years (*Table 1*). The significantly higher grain (11881 kg ha^{-1} and 11777 kg ha^{-1}) in 2017 and 2018 were recorded due to the addition of organic matter by straw application (Christensen, 1986) under the SI+ST treatment. The treatment SI+ST gave a 2.9% higher dry matter over the SI treatment (*Fig. 1*). Our findings agree with Zhang et al. (2015), who have found that straw incorporation increased grain yield and biomass yield. Therefore, the application of Si with straw return should be considered an essential practice in maize farming for improving yield and promoting sustainable soil systems.

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Total plant N uptake and uptake rate

Cuong et al. (2017) noted that the application of Si at the level of 329 kg hm^{-2} with inorganic fertilizer would help in N uptake in rice. Si and N are said to have a synergistic effect, and Si can raise the optimum N rate in rice (Ho et al., 1980). Averaged over two years, the N uptake rate under the SI treatment increased by 10.4% than that under the C treatment (*Table 4*). We also found that the application of Si increased N uptake by 15.6% on average compared with the N uptake under the conventional practice (C) (*Fig. 2*). Our findings concerning the significant effect of Si to N uptake are broadly in line with Laîné et al. (2019).

Table 4. *Logistic equation characteristics (Eq.1,2 and 3) of the N uptake of the entire plant subjected to different Si and straw treatments in 2017 and 2018. t_1: Time of total plant N uptake acceleration t_2: Time of whole plant N uptake deceleration T: The fast uptake period of total plant N (d)*

Years	Treatments	Regression equation	R^2	t_1 (day)	t_2 (day)	T (day)	Uptake rate (kg ha^{-1}d^{-1})
2017	C	N=188.8/(1+60.1e$^{-0.0714t}$)	0.9970*	38.9	75.8	36.9	2.95d
	SI	N=220.6/(1+68.8e$^{-0.0669t}$)	0.9981*	43.6	82.9	39.4	3.24b
	ST	N=205.8/(`1+56.8e$^{-0.0693t}$)	0.9940*	39.3	77.3	38.0	3.13c
	SI+ST	N=236.6/(1+89.4e$^{-0.0657t}$)	0.9989*	48.3	88.4	40.1	3.41a
2018	C	N=164.8/(1+188.7e$^{-0.0746t}$)	0.9901*	53.6	87.9	34.3	2.71d
	SI	N=192.2/(1+336.6e$^{-0.0714t}$)	0.9856*	63.1	99.9	36.9	3.01b
	ST	N=174.6/(1+390.4e$^{-0.0744t}$)	0.9872*	62.5	97.9	35.4	2.85c
	SI+ST	N=213.4/(1+390.4e$^{-0.069t}$)	0.9848*	67.4	105.6	38.2	3.23a

*, significant at P<0.05; **, significant at P<0.01

Appropriate incorporation of straw has a positive effect on N mineralization and probably N uptake by rice crop (Takahashi et al., 2003). Zhang et al. (2016) demonstrated that the use of compost plus inorganic fertilizer as a practical nutrient management approach to maintain N uptake, reduce N loss and, increase soil fertility. It is evident from our study that straw return significantly improved N uptake by crop (*Table 4*). The N uptake rate under the SI+ST treatment increased by 3.8% on average than that under the SI treatment. Similarly, in treatment with the straw application (SI+ST), N uptake was 7.6% higher than that with no straw treatment (SI) (*Fig. 2*). Similar results have been reported by Hu and Zhang (2017) that straw incorporation improved N uptake and NUE in rice.

Remobilization of N in spring maize

During the vegetative phase, the leaves and stem are the sinks for N; later, during senescence or deficiency periods, this N is re-translocated for reuse in the developing grain, fruits, and even young leaves (Okumoto and Pilot, 2011; Hernandez-Apaolaza, 2014). A balanced input of N and Si fertilizers showed an effect on agronomic indexes of rapeseed crops (Laîné et al., 2019). In this study, the remobilization amount, remobilization efficiency, and contribution to the grain under SI treatment increased by 21%, 4%, and 6.8%, respectively, compared to that under C (*Table 2*). The increase of remobilization under SI treatment was probably due to the application of Si fertilizer

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stimulated plants to take up more N (Neu et al., 2017) for remobilization. Our study corroborates with Detmann et al. (2012), who demonstrated that Si nutrition promoted N remobilization by stimulating amino acid remobilization from vegetative parts to the grains. Straw incorporation has the potential to affect agricultural management practices that improves soil nutrients (Zhou et al., 2018) as it is a readily available organic material which function to enhance soil fertility by releasing some nutrients such as N.P.K and others (Pathak et al., 2006). Organic matter applied in the form of liquid cattle manure increased N accumulation, distribution, and remobilization from leaves and stem to kernels (Dordas et al., 2008). In our study, straw application significantly affected the re-translocation of N (*Table 2*). The SI+ST treatment increased by 7.9%, 1.1%, and 3.6% of N remobilization amount, remobilization efficiency, and N contribution to the grain, respectively, compared with that of the SI treatment. This study supported previous reports Wang et al. (2017) that manure plus urea improved N accumulation and remobilization in wheat.

Si fertilization under straw return improved the NUE of maize

The Si nutrient modified nitrogen (N) use efficiency (NUE) in rice (Yogendra et al., 2013; Cuong et al., 2017) and wheat (Yogendra et al., 2013). Higher NUE observed with the application of calcium silicate (Yogendra et al., 2013). This study has clearly shown a significant effect of Si fertilizer on the NUE of maize. In the plot that received 45 kg ha^{-1} of sodium silicate, the agronomic N use efficiency (AEN), recovery N use efficiency (REN), and partial factor productivity of N (PFPN) was 13.6%, 44.9%, and 4.9%, respectively higher than that in the conventional practice plot (C). However, Si fertilizer under SI treatment decreased the physiological efficiency of N (PEN) in our results by 26.7% than that under the C treatment (*Table 3*). The result shows that there was a synergistic effect between Si and N. This study was consistent with the results of Si and N fertilization in rice (Yogendra et al., 2014) and in wheat (Neu et al., 2017) that Si fertilizer enhances the NUE's except for the PEN. Moreover, the PEN decreased with the addition of Si fertilizer, which was in harmony with the findings of (Awgchew et al., 2017), who revealed a reduced PEN with increases of fertilizer. The main reason for this phenomenon may be that the amount of nitrogen absorbed by the leaves and stems on the ground is much higher than that of the control, which reduces the yield of grain per unit of nitrogen.

Straw return and appropriate tillage approach significantly enhanced grain yield and NUE in winter wheat (Jin et al., 2017). The inorganic fertilizer, coupled with organic fertilizer, increases N uptake in rice by improving soil properties and NUE (Iqbal et al., 2019). In this study, as expected, the Si fertilizer and straw application had a significant effect on NUE. The AEN, REN, and PFPN of the SI+ST treatment were 3.6%, 17.6%, and 1.3% higher than that of SI treatment (*Table 3*). The increased NUE by straw was probably attributed to the improved organic matter status since straw served as N source (Kongchum et al., 2007). These results agree with the findings of previous studies that straw return significantly increased NUE (Eagle et al., 2000). Thus, retention of Si fertilizer plus straw return can be an option practice to improve NUE in agricultural production.

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Conclusion

The use of silicon fertilizer can not only improve the N uptake and the N uptake rate of maize, but also promote the remobilization of nitrogen and the apparent contribution to grain N, and ultimately improve the yield. In comparison to the sole Si fertilizer application, the application of silicon fertilizer with straw return can further enhance the above effects, and at the same time, improve agronomic use efficiency, recovery use efficiency, and N partial factor productivity. There is sufficient evidence to support the claim that Si fertilizer combined with straw was of great advantage not only at improving NUE and crop yield but also reducing the effect of fertilizer on the environment, thus attaining the goals of sustainable agriculture. In further studies, long term experiments on Si fertilizer with straw return should be conducted to get more data that can provide comprehensive results on the integration of Si fertilizer and straw return on N nutrient. In addition, more studies should focus on how straw materials can be used to replace the use of Si fertilizer.

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