EFFECT OF DIFFERENT RESOURCES AND METHODS OF SILICON AND ZINC APPLICATION ON AGRONOMIC TRAITS, NUTRIENT UPTAKE AND GRAIN YIELD OF RICE (*ORYZA SATIVA* L.)

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Abstract. To evaluate the effect of different resources and methods of silicon (Si) and zinc (Zn) application on agronomic traits, nutrient uptake and grain yield of rice (*Oryza sativa* L.), a field experiment was conducted as a randomized complete block design with 16 treatments and three replications in Noor region, Mazandaran province, Iran in the crop year of 2015-2016. The experimental treatments included the different resources and forms of Si and Zn application as nanoparticles (NPs) foliar application and soil application of the elements. The results indicated that grain and straw yields were increased in response to application of Si and Zn fertilizers. All fertilized treatments had significantly higher yields than the control, although yields did not differ significantly between the fertilized treatments. The experimental treatments significantly affected the yield components, Si, Zn and N concentrations in the plant tissue. The combined application of Si and Zn by both methods, either via NPs foliar application or soil application resulted in an increase in the grain and straw yields, yield components and Si, Zn and N concentrations in rice grain and straw. According to the results of this research, the combined application of Si plus Zn, especially by NPs foliar application, is appropriate for increasing the production of the rice crop in Noor Region of Iran.

Keywords: *crop yield, foliar application, rice, soil application, silicon, zinc*

Introduction

Silicon (Si) and zinc (Zn) as macro and micronutrients, respectively have a key role in improving growth and increasing grain yield of plants, and their deficiency can make a serious problem for crop production, especially in the case of rice. Silicon is the second most abundant mineral in the soil (Kafi and Rahimi, 2011), that is a useful nutrient for healthy growth and sustainable production of rice (Tamai and Ma, 2008). Silicon has a dual effect on the plant and soil system, which, by being absorbed in the plant, makes the plant more resistant to pests, diseases and environmental stresses, and, on the other hand, led to soil fertility by improving water, physicochemical properties of soil and maintaining the nutrients in available form for the plant (Meena et al., 2014). Soil silicon has several benefits for rice including the reduction of the adsorption of heavy metals such as Pb (Jianguo et al., 2015), Cd (Lin et al., 2016), and As (Wu et al., 2015), resistance to salt stress (Mahmoud et al., 2017), increasing the extent of photosynthesis, the improvement of performance, the prevention of lodging (Jeer et al., 2017), as well as the reduction of the negative effects of ultraviolet radiation on the

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physiological processes of photosynthesis and transpiration (Lou et al., 2016). The modern silicon fertilizers (nano-SiO2) easily penetrate into the leaves and create a thick silicate layer on the leaf surface (Meena et al., 2014). Silicon plays an important role in increasing the activity of antioxidant enzymes and enhancing the content of osmolites, in contributing to the resistance of abiotic and biotic stresses in plants (Amiri et al., 2014). Reports indicated that the use of Si increases the grain yield of rice by increasing the number of whole spikelets (Mobasser et al., 2008) and the number of fertile tillers per hill (Ghasemi Mianaei et al., 2011). Other researchers reported that the Si application significantly increased the tiller number and Si concentration in the plant (Zia et al., 2017). Cuong et al. (2017) reported that increase in Si application, increases the Si absorption and other nutrients such as nitrogen, phosphorus and potassium in rice biomass (grain + straw) compared to control.

Zinc, after nitrogen and phosphorus, is the most important nutrient that limits the grain yield of rice (Yakan et al., 2000), and is a global concern for human nutrition (Farooq et al., 2018). Zinc as a cofactor of antioxidant enzymes such as catalase and peroxidase plays an important part in plant protection and ultimately improves yield (Samart et al., 2017). Zinc has an important role in several physiological processes of the plants such as protein synthesis, enzyme activation, gene expression and carbohydrate metabolism (Chang et al., 2005; Qiao et al., 2014). Studies have shown that zinc improves the absorption of other nutrients such as potassium, phosphorus and iron for the plant (Amirjani et al., 2014). It has been reported that the application of nano-ZnO in the rates of 25 and 50 $mg.l^{-1}$ improves the rice growth (Upadhyaya et al., 2014), but in higher concentrations due to the creation of toxicity by the accumulation of this element in the plant lead to reduction in plant growth and biomass (Boonyanitipong et al., 2011; Chen et al., 2015). The improvement of zinc concentration and enhancement of rice grain yield by Zn supply through soil (basal) + 2 foliar applications have been reported in the results of other investigators (Saha et al., 2017). In a study, which the effects of zinc were evaluated by two methods of foliar application and soil application on yield and yield components of rice, reported that the number of fertile tillers, number of grains per panicle, 1000-grain weight, grain yield, harvest index and grain Zn concentration significantly increased compared to control using both methods (Farooq et al., 2018). Sudha and Stalin (2015) found that zinc application in soil with its foliar application significantly increased the agronomic and physiological traits.

The problem of accessibility to nutrients such as Si and Zn by usual methods results in an increase in the attention to the use of modern methods for application of these elements in recent years. Nanotechnology is one of the most modern methods in agricultural practices. The most important of its applications in different aspects of agriculture, that is in the water and soil section are the use of nano-fertilizers for plant nutrition (Mazlomi et al., 2012). Nanofertilizers are more effective in improving plant nutrition, increasing the efficiency of nutrient use, and protecting plants from environmental stresses than conventional fertilizers (Wang et al., 2015). The Maximum use of production sources, especially with the nano-fertilizers application, and enhancing photosynthesis efficiency can reduce the environmental risks associated with the excessive application of chemical fertilizers (Sepehri and Vaziri Amjad, 2015). Although nanotechnology in agriculture is less developed due to lower investment compared to other sectors, nanotechnology is very effective in improving agricultural production (Huang et al., 2015).

Therefore, the aim of the present study was to evaluate the effects of Si and Zn by applying different resources and methods to improve yield components, nutrient uptake and grain yield of rice.

Materials and methods

Experimental site

The field experiment was conducted during crop year of 2015-2016 in Noor region, Mazandaran province, Iran, located at 36° 46'N latitude, 52° 28'E longitude and 71 m above the sea level (*Fig. 1*). The meteorological data recorded during rice-growing seasons are presented in *Table 1*. The physical and chemical properties of the soil in the experimental site are shown in *Table 2*.

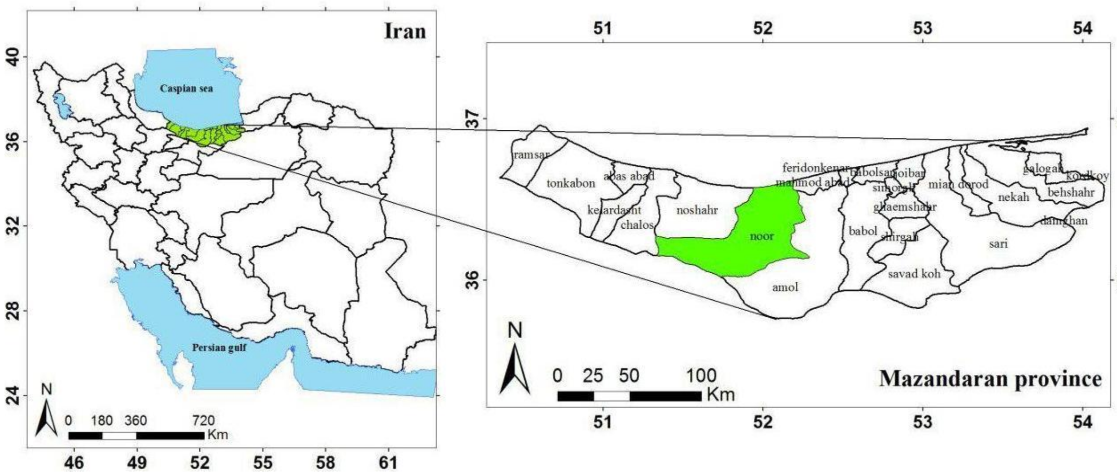

Figure 1. *The study area location in Noor region, Mazandaran province, Iran*

Table 1. *Meteorological data recorded during rice-growing seasons of the experiment*

Month of the year	Average of monthly temperature (°C)		Average of monthly relative humidity (%)		Total monthly rainfall (mm)	Total sunny hours (h)
	Minimum	Maximum	Minimum	Maximum		
March-April	10.4	17.3	67	94	129.8	121.1
April-May	15.5	21.4	73	94	43.0	159.3
May-June	19.4	26.0	67	90	27.7	260.8
June-July	22.6	28.8	67	89	179.9	208.9
July-August	23.2	30.1	68	90	46.1	251.1
August-September	22.0	29.3	66	90	182.6	205.9

Table 2. *Physical and chemical characteristics of the soil in the experimental site in a depth of 0-30 cm*

Soil texture	Silt (%)	Clay (%)	Sand (%)	pH	EC ($ds.m^{-1}$)	SP (%)	O.C (%)	O.M (%)	P ($mg.kg^{-1}$)	K ($mg.kg^{-1}$)	Zn ($mg.kg^{-1}$)	Si (%)
Loam	44	20	36	7.51	3.02	63	1.66	2.86	10.5	116	0.81	0.28

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Experimental layout, design and treatments

This experiment was designed as a randomized complete block design with 16 treatments and 3 replications, thus there were 48 equal plots in size of 10 m^2 (5 m × 2 m). The experimental treatments characteristics are presented in *Table 3*.

Table 3. *The experimental treatments characteristics*

Treatments	Treatments characteristics
T1	Control
T2	Soil application of calcium silicate
T3	Soil application of zinc sulfate
T4	Soil application of calcium silicate + zinc sulfate
T5	Foliar application of nano-SiO_2
T6	Foliar application of nano-SiO_2 + soil application of calcium silicate
T7	Foliar application of nano-SiO_2 + soil application of zinc sulfate
T8	Foliar application of nano-SiO_2 + soil application of calcium silicate + zinc sulfate
T9	Foliar application of nano-ZnO
T10	Foliar application of nano-ZnO + soil application of calcium silicate
T11	Foliar application of nano-ZnO + soil application of zinc sulfate
T12	Foliar application of nano-ZnO + soil application of calcium silicate + zinc sulfate
T13	Foliar application of nano-SiO_2 + nano-ZnO
T14	Foliar application of nano-SiO_2 + nano-ZnO+ soil application of calcium silicate
T15	Foliar application of nano-SiO_2 + nano-ZnO + soil application of zinc sulfate
T16	Foliar application of nano-SiO_2 + nano-ZnO + soil application of calcium silicate + zinc sulfate

The land preparation practices were performed according to the conventional procedure, so that the land was disk-ploughed in late February and the complete practices including puddling and leveling were carried out in mid-May. An indica rice (Oryza sativa L.) cultivar Tarom Hashemi was used as plant material for the present research, which is an early rice cultivar that usually used by farmers in the north of Iran. The seed of rice cultivar Tarom Hashemi was obtained from the Rice Research Institute, Mazandaran, Iran. Rice seedlings were transplanted at a spacing of 20 cm× 20 cm with four seedlings per hill in mid-May, and harvested in mid-August. For all treatments, phosphorus and potassium fertilizers were applied as basal at the rate of 70 kg ha^{-1} as triple superphosphate and 100 kg ha^{-1} as potassium sulfate, respectively. Urea was applied as nitrogen fertilizer uniformly for all the plots at the rate of 150 kg ha^{-1} in three equal splits (one third at the time of transplanting, one third at the tillering stage and one third at the heading stage). For soil application, silicon and zinc fertilizers were applied as basal at the rate of 400 kg ha^{-1} as calcium silicate and 40 kg ha^{-1} as zinc sulfate, respectively. For foliar application, nano-SiO_2 and nano-ZnO in the concentration of 50 mg L^{-1} was applied in four stages of plant growth (early tillering stage, middle tillering, panicle initiation and full heading stage) in plots. Nanofertilizers used in the experiment were products of US Research Nanomaterials, Inc (*Table 4*). In order to control the weeds during growing stages, manual weeding was performed twice on days 14th and 28th after transplanting, and for its chemical control, Butakler’s herbicide was applied in the concentration of 3.5 L ha^{-1} a week after transplanting. Furthermore, in order to control *Chilo suppressalis*, diazinon insecticide (10% granule) was used at a rate of 15 kg ha^{-1} at the peak of tillering and heading stages (*Fig. 2*). The rice striped stem borer, *Chilo suppressalis*, is one of the most serious sources of damage to rice growth and production in Asia, northern Africa, and southern Europe (He et al., 2014).

Table 4. *Analysis of silicon dioxide (SiO_2) and zinc oxide (ZnO) nanoparticles*

NPs	Purity percentage	Particles size	True density	Color
Sio_2	>99%	20-30 nm	2.4 g/cm^3	white
ZnO	>99%	10-30 nm	5.606 g/cm^3	Milky white

Figure 2. *Photos of experimental field and fertilizer treatments application in growth stages of rice*

Sample preparation and Si, Zn and N analysis

During the flowering stage of the plant, chlorophyll content of flag leaf was measured using chlorophyll meter (SPAD-502, Minolta, Japan). At maturity, determination of plant height and panicle length were performed by measuring 12 plants in each plot. The number of fertile tillers per hill was determined by counting from 12 hill per plot, number of filled and unfilled grains per panicle were determined by counting from 20 panicles per plot and 1000-grain weight was determined by counting and weighing 10 samples of 100 seed. Grain and straw yields were determined by manually harvesting each plot (2 × 2 m^2), separating grains from straw and drying samples in an oven at 70 °C for 48 h. Grain and straw samples were weighed with 14% moisture content and calculated based on kilograms per hectare.

Si concentration in plant samples (grain and straw) was determined by Yoshida method (Yoshida, 1975). Zn concentration in plant tissue was determined by Atomic Absorption Spectrophotometer (AAS) method (Emami, 1996). The N concentration in grain and straw was measured by micro-Kjeldahl method (Emami, 1996). Mobilization efficiency index (MEI) of Si, Zn and N was calculated as *Equations 1, 2* and *3:*

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$$Si\ MEI = \frac{\text{Si concentration in grain (\%)}}{\text{Si concentration in straw (\%)}} \tag{Eq.1}$$

$$Zn\ MEI = \frac{\text{Zn concentration in grain (mg.kg}^{-1}\text{)}}{\text{Zn concentration in straw (mg.kg}^{-1}\text{)}} \tag{Eq.2}$$

$$N\ MEI = \frac{\text{N concentration in grain (\%)}}{\text{N concentration in straw (\%)}} \tag{Eq.3}$$

where Si = silicon, Zn = zinc, N = nitrogen, and MEI = mobilization efficiency index.

The mobilization efficiency index of the elements was calculated to determine the amount of transmission of these elements from straw to grain and their accumulation in grain.

Statistical analysis

The data were statistically analyzed using MSTATC software. Randomized complete block design was used for data analysis. The mean comparison was performed using the least significance difference (LSD) test at 5% probability level. A simple linear regression was used to determine the relationship between the concentrations of Si and Zn in grain and straw with N concentrations in rice plant tissue and its yields.

Results

Grain and straw yields

In this study, grain and straw yields were increased in response to application of Si and Zn fertilizers. All fertilized treatments had significantly higher yield than the control, although its yield did not differ significantly between the fertilized treatments. The maximum grain yield (4502 kg ha^{-1}) and straw yield (5933 kg ha^{-1}) were obtained by the application of T13 (nano-SiO2 + nano-ZnO) and T16 (nano-SiO2 + nano-ZnO + calcium silicate + zinc sulfate) treatments, respectively. However, the combined application of Si and Zn had better effect in increasing grain and straw yields compared to individual application of each element (*Table 5*). There was a positive and significant linear correlation between rice grain and straw yields with the Si and Zn concentration in grain and straw at a probability level of 1%, such that by increasing Si concentration in grain and straw ($R^2 = 0.1588$ and $R^2 = 0.0714$, $P < 0.01$, respectively), and Zn concentration in grain and straw ($R^2 = 0.1749$ and $R^2 = 0.2173$, $P < 0.01$, respectively), grain and straw yield increased (*Fig. 3*).

Plant height and panicle length

In this research, the plant height did not differ significantly comparing experimental treatments. While, the panicle length was significantly affected by the evaluated treatments. The panicle length was significantly increased by combination of both methods of NPs foliar application and soil application in different treatments, but the maximum panicle length (26 cm) was obtained by the foliar application of nano-SiO_2 + nano-ZnO (T13), while the minimum panicle length (21.67 cm) was obtained in the control or no fertilizer application (*Table 6*).

Table 5. *Mean comparison of effect the experimental treatments on grain and straw yields of rice (cv. Tarom Hashemi)*

Treatments	Grain yield (kg.ha^{-1})	Straw yield (kg.ha^{-1})
T1	3503b	4845b
T2	3834ab	5316ab
T3	4053ab	5477a
T4	4170ab	5602a
T5	4031ab	5496a
T6	4000ab	5370ab
T7	4210ab	5543a
T8	4358ab	5477a
T9	4133ab	5337ab
T10	4121ab	5389ab
T11	4243a	5692a
T12	4293a	5763a
T13	4502a	5917a
T14	4400a	5827a
T15	4388a	5853a
T16	4423a	5933a
LSD$_{0.05}$	717	626.7

Values followed by different small letters within columns are significantly different ($p < 0.05$) according to the LSD test

Table 6. *Mean comparison of the effects of experimental treatments on agronomic traits of rice (cv. Tarom Hashemi)*

Treatments	Plant height (cm)	Panicle length (cm)	No. of fertile tillers hill^{-1}	No. of filled grain panicle^{-1}	No. of unfilled grain panicle^{-1}	1000-grain weight (g)	Chlorophyll content
T1	135.2a	21.67d	13.13h	81.53f	20.60ab	25.33a	35.03c
T2	137.3a	23.23c	15.03g	88.03b-f	15.93c-f	25.50a	35.43bc
T3	138.4a	24.40bc	16.03efg	87.60c-f	15.30c-f	25.60a	36.20abc
T4	138.3a	25.53ab	16.57b-f	97.07ab	15.43c-f	25.20a	36.07abc
T5	138.9a	25.67ab	15.90efg	85.80def	18.27bc	25.67a	35.70abc
T6	140.1a	25.50ab	15.53fg	100.0a	12.90ef	25.00a	36.40abc
T7	139.0a	25.80ab	16.50c-f	94.10a-d	17.00bcd	25.50a	37.03abc
T8	139.8a	25.93a	16.73b-f	95.00a-d	16.50cde	25.47a	36.90abc
T9	140.1a	25.80ab	16.50c-f	90.93a-e	15.00c-f	25.73a	36.30abc
T10	138.5a	25.70ab	16.37d-g	94.40a-d	13.73def	25.60a	36.70abc
T11	139.2a	25.57ab	17.07a-e	83.50ef	22.80a	25.73a	36.63abc
T12	140.8a	25.77ab	17.13a-e	88.93b-f	17.00bcd	25.50a	37.67ab
T13	138.5a	26.00a	18.47a	93.90a-d	13.37def	25.63a	37.33abc
T14	141.0a	25.93a	17.70a-d	95.50abc	12.60f	25.57a	37.00abc
T15	139.7a	25.83a	17.83abc	90.23b-f	16.37cde	25.77a	37.77ab
T16	143.2a	25.87a	18.00ab	87.37c-f	16.10c-f	25.87a	38.00a
LSD$_{0.05}$	10.24	1.431	1.447	9.307	3.722	1.396	2.343

Values followed by different small letters within columns are significantly different ($p < 0.05$) according to the LSD test

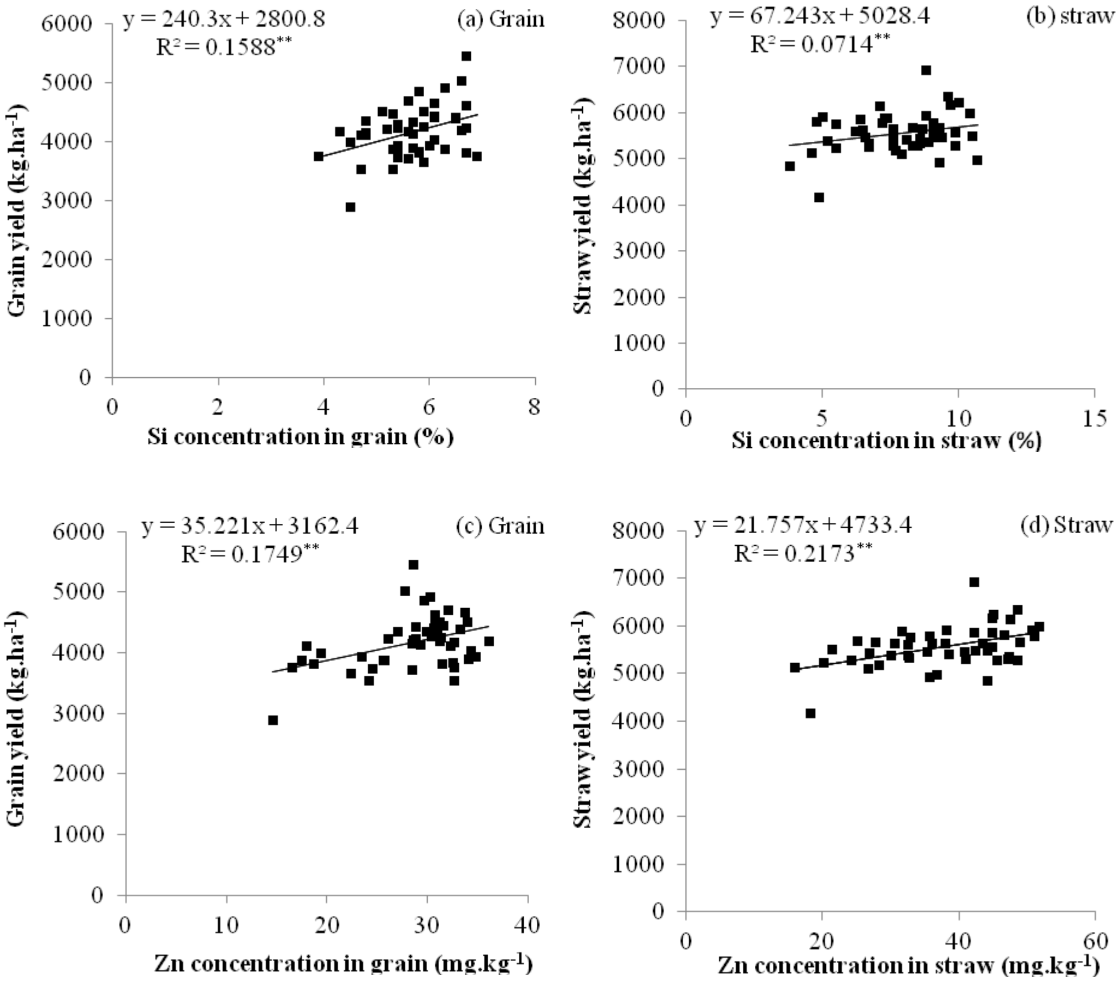

Figure 3. *The relationship of Si concentration in grain (a) and straw (b) with grain and straw yields of rice, correlations of Zn concentration in grain (c) and straw (d) with grain and straw yields of rice under the influence of experimental treatments*

Fertile tiller number per hill

Si and Zn application significantly increased the number of fertile tiller per hill. The maximum fertile tiller number per hill (18.47 tiller) was obtained by simultaneous foliar application of nano-SiO_2 + nano-ZnO (T13), and this trait was reduced under control condition by 28.9% (*Table 6*).

Filled and unfilled grain number, 1000-grain weight

The results of this experiment showed that the number of filled and unfilled grains per panicle were significantly affected by the experimental treatments. The highest number of filled grains per panicle (100 whole grain) was obtained by combined application of nano-SiO_2 foliar spray + calcium silicate soil application (T6), and with no fertilizer application (control), the trait was reduced by 18.4%. Also, the lowest number of unfilled grain per panicle was observed in the treatments of T6 and T14. The effect of experimental treatments was not significant on 1000-grain weight (*Table 6*).

Chlorophyll content of flag leaf

By Si and Zn application the chlorophyll content of flag leaf improved compared to the control, such that the maximum chlorophyll content (38.00) was obtained by T16 treatment application, whereas without applying Si and Zn, this trait was reduced by 7.8% (*Table 6*).

Si concentration in grain and straw

A significant increase in Si concentration in plant tissue was observed by NPs foliar application and soil application of elements. Mean comparison indicated that the Si concentration in grain (6.40%) and straw (9.80%) of rice was significantly increased by combined application of Si and Zn in both methods of NPs foliar application and soil application (T16). The lowest Si concentration in grain and straw of rice was observed in the control or no fertilizer application (T1). The application of T9 treatment increased the Si mobilization efficiency index (1.01) because of the better transfer of Si from straw to seed and consequently its accumulation in grain (*Table 7*).

Table 7. *Mean comparison of the effects of experimental treatments on Si concentrations in grain and straw of rice (cv. Tarom Hashemi)*

Treatments	Si concentration in grain (%)	Si concentration in straw (%)	Si MEI
T1	4.60e	5.40e	0.85ab
T2	5.36a-e	6.63de	0.81ab
T3	4.93de	6.00e	0.82ab
T4	5.60a-e	7.10b-e	0.79ab
T5	5.83a-d	8.60a-d	0.67b
T6	6.00abc	9.00abc	0.66b
T7	5.90a-d	8.80abc	0.68b
T8	6.30ab	9.40a	0.66b
T9	5.33b-e	5.80e	1.01a
T10	5.46a-e	7.00cde	0.82ab
T11	5.03cde	6.30e	0.85ab
T12	5.70a-d	7.33b-e	0.77ab
T13	6.00abc	9.06ab	0.66b
T14	6.36ab	9.50a	0.66b
T15	6.10ab	8.91abc	0.68b
T16	6.40a	9.80a	0.64b
$LSD_{0.05}$	1.056	2.010	0.2983

Values followed by different small letters within columns are significantly different ($p < 0.05$) according to the LSD test

Zn concentration in grain and straw

The effect of experimental treatments was significant on Zn concentration in rice plant tissue. However, by combined application of Si and Zn in the form of soil and foliar application, Zn concentration was increased in grain and straw. The maximum Zn concentration in grain (32.90 $mg.kg^{-1}$), was obtained by treatments of T16, while the maximum Zn concentration in straw (48.80 and 48.50 $mg.kg^{-1}$) was obtained by treatments of T15 and T16, respectively. Zn mobilization efficiency index did not differ significantly in the fertilized treatments (*Table 8*). According to *Figure 4,* the Zn concentration changed by changes in Si concentration, such that by increasing Si concentration in plant tissue, Zn concentration in grain and straw increased ($R^2 = 0.1664$ and $R^2 = 0.1642$, $P < 0.01$, respectively).

Table 8. *Mean comparison of the effects of the experimental treatments on Zn concentrations in grain and straw of rice (cv. Tarom Hashemi)*

Treatments	**Zn concentration in grain ($mg.kg^{-1}$)**	**Zn concentration in straw ($mg.kg^{-1}$)**	**Zn MEI**
T1	16.20e	19.50h	0.84a
T2	21.63d	25.90gh	0.87a
T3	27.80bc	34.50d-g	0.81a
T4	28.40abc	36.30c-f	0.79a
T5	23.70cd	28.20fgh	0.84a
T6	24.20cd	28.70efg	0.89a
T7	30.30ab	37.50b-e	0.82a
T8	30.50ab	38.30bcd	0.79a
T9	30.30ab	38.50bcd	0.79a
T10	30.60ab	40.40a-d	0.76a
T11	31.70ab	42.10a-d	0.75a
T12	31.50ab	43.60abc	0.72a
T13	31.80ab	45.20abc	0.69a
T14	32.00ab	46.20ab	0.69a
T15	32.60ab	48.80a	0.66a
T16	32.90a	48.50a	0.67a
$LSD_{0.05}$	4.944	9.026	0.2529

Values followed by different small letters within columns are significantly different ($p < 0.05$) according to the LSD test

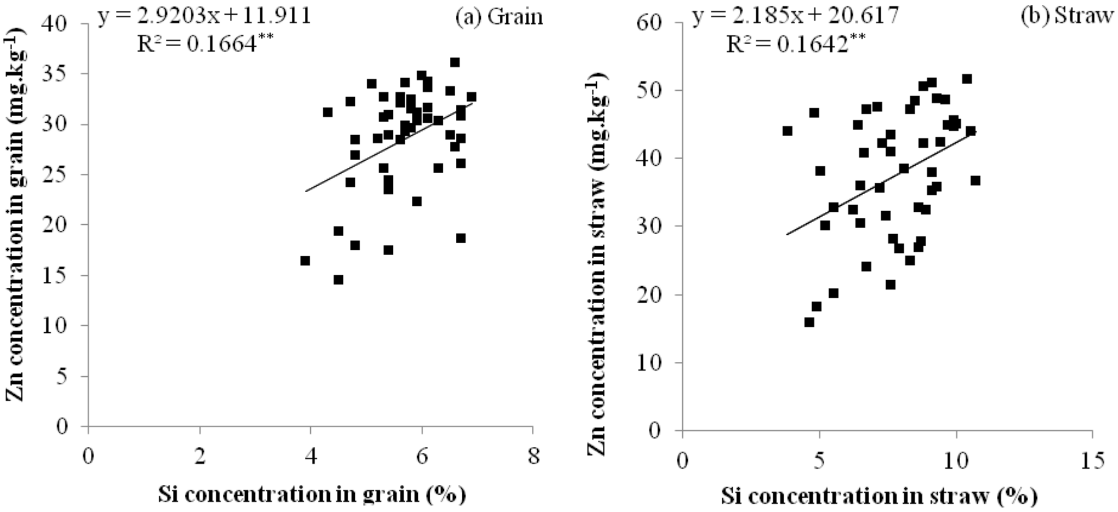

Figure 4. *The relationship of Si concentration in grain (a) and straw (b) and Zn concentration in grain and straw of rice under experimental treatments*

N concentration in grain and straw

The N concentration in grain and straw was increased by Si and Zn application. The NPs foliar application and soil application of Si and Zn significantly improved the N concentration in plant tissue compared to control. The maximum N concentration in grain was obtained by treatments of T14, T15 and T16. Also, the T15 and T16 treatments had the highest N concentration in rice straw. The maximum N mobilization efficiency index in rice plant was observed by T1 treatment or control (*Table 9*). There was a positive and significant linear correlation between N concentrations in plant tissue with the Si and Zn concentration in grain and straw at a probability level of 1%, such that by increasing Si concentration in grain and straw ($R^2 = 0.0655$ and $R^2 = 0.1859$, $P < 0.01$, respectively), and Zn concentration in grain and straw ($R^2 = 0.1902$ and $R^2 = 0.4708$, $P < 0.01$, respectively), N concentrations in grain and straw increased (*Fig. 5*).

Table 9. *Mean comparison of the effects of the experimental treatments on N concentrations in grain and straw of rice (cv. Tarom Hashemi)*

Treatments	N concentration in grain (%)	N concentration in straw (%)	N MEI
T1	1.36c	0.569d	2.40a
T2	1.39bc	0.622cd	2.25ab
T3	1.43abc	0.670bcd	2.14ab
T4	1.44abc	0.718abc	2.01ab
T5	1.43abc	0.656bcd	2.18ab
T6	1.43abc	0.668bcd	2.13ab
T7	1.46abc	0.751abc	1.95b
T8	1.47abc	0.767ab	1.97b
T9	1.45abc	0.718abc	2.03ab
T10	1.48abc	0.707abc	2.09ab
T11	1.50abc	0.739abc	2.03ab
T12	1.51abc	0.774ab	1.96b
T13	1.51ab	0.785ab	1.94b
T14	1.54a	0.780ab	1.97b
T15	1.54a	0.823a	1.90b
T16	1.55a	0.816a	1.90b
$LSD_{0.05}$	0.1491	0.1292	0.3981

Values followed by different small letters within columns are significantly different ($p < 0.05$) according to the LSD test

Discussion

The increase of the grain and straw yields with simultaneous application of Si and Zn can be attributed to the positive and synergistic effects between silicon and zinc, which by increasing the Si and Zn uptake, as well as increasing the fertile tiller number per hill lead to an increase in yields. There were synergistic interactions between Si and Zn, which ultimately has contributed to increased absorption of these elements in the plant tissue (Ghasemi et al., 2014). In the present study, in terms of an increase in yields, the NPs foliar application slightly is better than soil application of these elements. The micronutrients in the form of nanoparticles are effective in producing and increasing the product yield (Reynolds, 2002). Amrullah et al. (2015) stated that nano-SiO_2 is superior over conventional silicon fertilizer. Gradual release of nutrients during growth stages of the plant by nano-ZnO application increases growth and rice yield (Yuvaraj and Subramanian, 2014). Cuong et al. (2017) reported that by adding silicon, rice grain yield was improved due to increasing growth, yield components, and better absorption of nutrients. Silicon application, especially at reproductive stages increases the chlorophyll content, the number of fertile tiller per hill, percentage of filled spikelets, and finally improves rice grain yield (Tamai and Ma, 2008). Zinc application by both methods foliar application and soil application is suitable for improving grain yield and increasing profitability in various systems of rice production (Farooq et al., 2018). Saha et al. (2017) revealed that zinc supply through soil + 2 foliar application caused the greatest increase in zinc concentration in rice grains by producing optimal grain yield, which confirms the results of the present study.

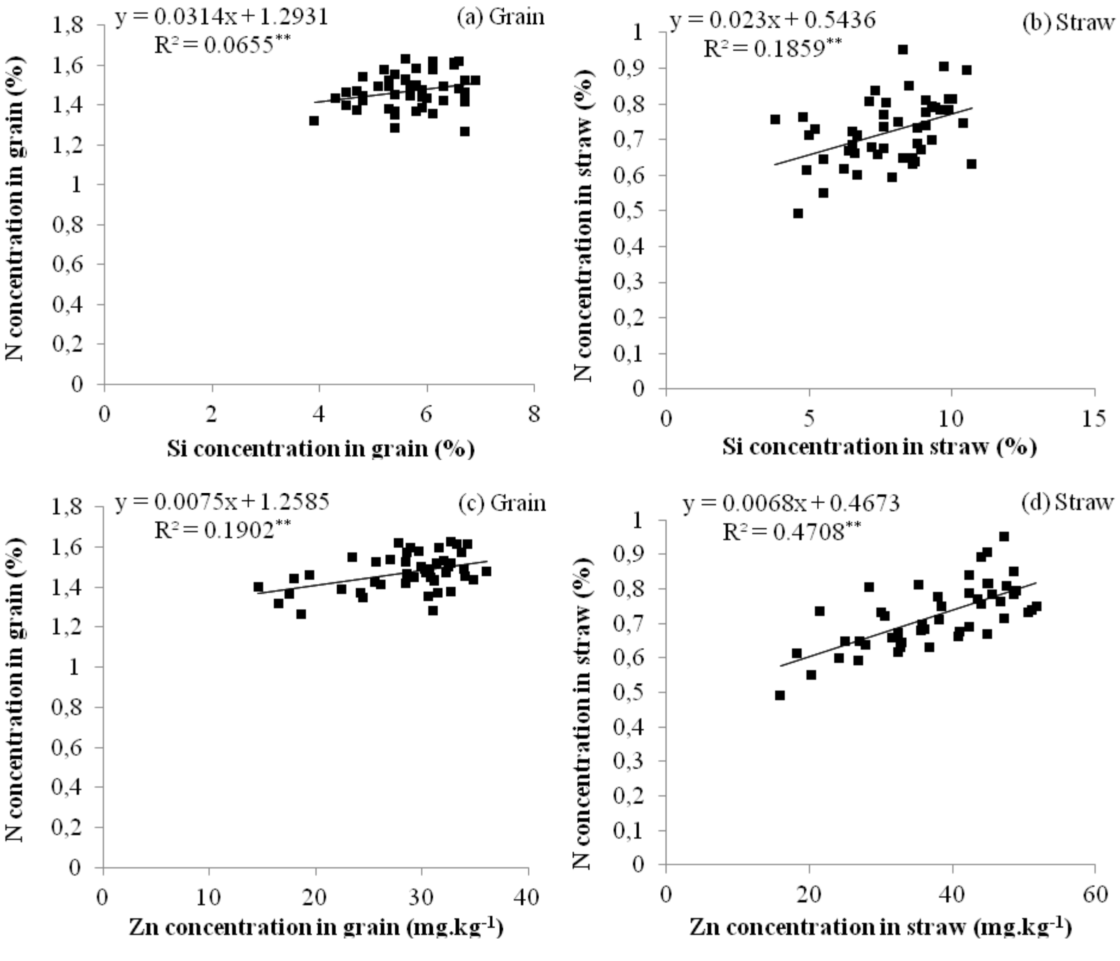

***Figure 5.** The relationship of Si concentration in grain (a) and straw (b) and N concentration in grain and straw of rice, correlations of Zn concentration in grain (c) and straw (d) with N concentration in grain and straw of rice under experimental treatments*

It seems that the soil application of Si and Zn was less effective in improving panicle length than NPs foliar application, although it increased the trait compared to control. Although panicle length does not directly have a role in the calculation of grain yield, it is considered as one of the yield evaluation attributes (Jalali et al., 2015). Ghasemi Lamraski et al. (2014) reported that foliar application of nano-SiO_2 caused a 1.4% increase in the panicle length compared to non-silicon application. According to Kamari et al. (2014) by foliar application of nano-ZnO significantly increased the panicle length of triticale.

By combined application of Si and Zn in both methods used, the number of fertile tillers per hill significantly increased compared to individual application of Si and Zn. Zia et al. (2017) reported that the proper use of silicon has been effective in increasing the number of rice tillers, such that the application of 3 mM of silicon caused a 19% increase in the number of tiller compared with the control. Application of zinc in both methods of soil and foliar application due to increased zinc concentration in plant leads to an increase in the number of effective tillers per square meter (Farooq et al., 2018). The supply of silicon and zinc by the plant through NPs foliar application increased the number of fertile tillers per hill compared to the soil method. In similar results, the researchers by studying different sources of silicon in the methods of soil and NPs foliar application reported that the maximum fertile tiller number per hill was obtained by nano-SiO_2 foliar application for two crop years (Yazdpour et al., 2014a). The positive effect of zinc on increasing the number of fertile tillers per hill was quite evident over silicon so that in all treatments where zinc fertilizer was used to forms of NPs foliar application and soil application, the fertile tiller number was improved compared to silicon application, although using both elements increased the number of the fertile tiller per hill.

Reduction of the number of filled grains per panicle with no fertilizer application could be due to the lack of availability to nutrients and the reduction of photosynthetic seed distribution, but this trait was increased with the addition of Si and Zn. The result showed that the number of filled grains per panicle significantly increased in treatments where silicon was used. Cuong et al. (2017) reported that the number of grains per panicle was increased by increasing silicon application. The silicon application in the reproductive stages of rice had a very positive effect on the improvement of the number of filled grains per panicle (Lavinsky et al., 2016), which confirms the results of this experiment. According to Tamai and Ma (2008), among the yield components, the percentage of filled spikelets was more affected by silicon fertilizer.

The grain size in rice is controlled by its shell, which shows that why the extent of 1000-grain weight changes is not high (Saha et al., 1998). Reports indicate that the 1000-grain weight was not affected by different concentrations of silicon (Yazdpour et al., 2014a), which is consistent with the results of the present research. In contrast, a piece of research showed that the zinc application from different sources had a significant effect on thousand grain weight of rice (Shivay et al., 2016).

By combined application of Si and Zn in both methods of NPs foliar application and soil application, the chlorophyll meter value increased compared to the separate application of these two element. Nano-Si has an important role in increasing the chlorophyll content of rice leaves (Wang et al., 2015). It was reported that application of nano-Zn oxide did not significantly affect the photosynthetic pigment content of different varieties of rice, but it protected photosynthetic pigments such as chlorophyll a and b in plant cells by improving the antioxidant enzymes activities (Samart et al., 2017). Zinc foliar application at the tillering stage of rice led to an increase in gene expression, carbonic anhydrase enzyme activation, improvement of the photosynthesis process and increase in relative chlorophyll concentration per unit leaf area (Qiao et al., 2014). Several reports have been presented by investigators regarding the effects of Si (Ranganathan et al., 2006) and Zn (Kabeya and Shankar, 2013) on increasing the chlorophyll content of plants, which is consistent with the results of this study.

In the present research, Si application increased the Si concentration in grain and straw of rice, and Zn application plus Si led to higher concentrations of Si in rice tissue. Reports indicated that the Zn application in the root increases the Si concentration in root and shoot (Mehrabanjoubani et al., 2015). Zia et al. (2017) found that by increasing silicon consumption from 0 to 3 mM, the Si concentration in root and shoot was increased by about 48 and 42%, respectively. According to Yazdpour et al. (2014b) the highest Si concentration in rice was obtained by nano-Si foliar application in both years of study.

The Zn concentration in grain and straw was improved in all treatments in which Zn fertilizer was used to both methods of soil application and NPs foliar application. It has been reported that the zinc concentration in rice grains increased by 47% compared to control, when zinc fertilizer was applied through soil (basal) + foliar application at maximum tillering and flowering stages (Saha et al., 2017). Zinc application using four different methods (foliar application, soil application, seed priming and seed coating) significantly increased grain zinc concentration in various systems of rice production at two different sites (Farooq et al., 2018). Although the combined application of Si and Zn in soil application method led to an increase in grain and straw Zn, the effect of combined application of elements by NPs foliar application method was greater than soil application. Si application by methods of soil application and NPs foliar application individually or in a combination of two methods could not significantly increase the grain and straw Zn concentration, but the Si application plus Zn significantly increased zinc concentration in rice tissue due to the synergistic interaction of these two elements. Similar to the results of this experiment, in previous studies the increase of Zn concentrations in rice plant tissue by the nano-Si application was reported (Wang et al., 2015).

In this research, it seems that role of Zn in improving N concentration was slightly more than Si, although both elements were effective in improving N concentration. The Zn application increases the accumulation of amino acids and nitrogen metabolism in plant tissue (Sudha and Stalin, 2015). Reports indicate that the N uptake was improved by Zn application in two growing seasons (Kumar Naik and Kumar Das, 2008). The researchers revealed that there was a positive and significant linear relationship between the amount of silicon absorption and the uptake of nitrogen in rice plant (Cuong et al., 2017). According to Yazdpour et al. (2014b) the maximum N concentration and protein content of rice were obtained by the foliar application of nano-Si.

Conclusion

In this research, we investigated the effects of different resources and methods of silicon and zinc application on agronomic and physiological traits, as well as the grain and straw yield of rice in Mazandaran province. The results revealed that the application of Si and Zn in both methods of NPs foliar application and soil application had a positive effect on agronomic traits and seed yield, although the influence of Zn fertilizer on grain and straw yields improvement was slightly more than Si fertilizer. Also, in both methods, the foliar application of nanoparticles had better efficiency than soil application of the elements due to the small size of the particles and the ability to absorb more of the elements by the plant. By combined application of Si and Zn, many physiological characteristics such as the Si, Zn and N concentrations in rice plant tissue, yield components and grain and straw yield of rice improved compared to separate application of each elements and control. The main reason for this increase could be synergistic effects between the two elements of silicon and zinc, such that the silicon caused the balance of nutrients in the plant and was a good supplement with zinc in improving the nutrients uptake and increasing grain yield.

Therefore, given that the simultaneous application of silicon and zinc, especially by foliar application of nanoparticles provides the nutrient required for the plant and improves grain production of rice, this fertilizer treatment is recommended for use in soils similar to the one used in this experiment.

Future extensions of this study for future research: It is recommended to investigate the quality of rice produced in the cultivar studied in these treatments. The experimental treatments on late rice varieties can be also studied. Moreover, the germination characteristics of seeds produced in these treatments, as well as the effect of these treatments on the absorption efficiency of the main elements of NPK can be evaluated. Also, the effects of other nano-fertilizers such as nano-MgO and nano-Ag in combination with the nanoparticles used in this experiment, as well as the effects of other fertilizer sources containing silicon and zinc such as potassium silicate and zinc chelate on physiological traits, rice growth and yield can be investigated. Besides, the absorption of other essential nutrients such as P, K, S, Ca, Mg, Fe, Cu, Mn, B, as well as heavy metals such as Cd, As and Pb in rice grains can be measured in order to determine the health status of rice seeds because rice seeds are fed by humans. Finally, the effects of silicon and zinc both in the form of nanoparticles and conventional method on rice grain yield by a foliar application can be studied.

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