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Effect of Foliar Application of Phosphorus, Zinc, and Silicon Nanoparticles along with Mineral NPK Fertilization on Yield and Chemical Compositions of Rice (*Oryza sativa* L.)

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Abstract: The traditional techniques of adding fertilizers to soil have a number of drawbacks in regard to the availability of nutrients for plants. The foliar application of nanoparticles causes them to be absorbed easily, and consequently, this is the most efficient method of dealing with nutritional deficiencies, reducing rice disease, and enhancing crop production and quality. Moreover, by using less fertilizer on the soil, it minimizes environmental pollution and improves the efficiency of nutrient utilization. In order to assess the impact of foliar applications of phosphorus, zinc, and silicon nanoparticles (PNPs, ZnNPs, and SiNPs) combined with mineral nitrogen, phosphorus, and potassium (NPK) fertilizers as a basal application on the Egyptian Giza 179 rice variety, a field experiment was carried out in two consecutive growing seasons: 2019 and 2020. With four replications, a Randomized Complete Block Design was applied, which included N_{165}:P_{36}:K_{60} (Recommended NPK; 165 Urea: 36 P_2O_5: 60 K_2O kg ha^{-1}); N_{110}:P_{24}:K_{40} ($^2/_3$ NPK); $^2/_3$ NPK+ $PNPs_{1000}$; $^2/_3$ NPK+ $PNPs_{3000}$; $^2/_3$ NPK+ $PNPs_{5000}$; $^2/_3$ NPK+ $ZnNPs_{25}$; $^2/_3$ NPK+ $ZnNPs_{50}$; $^2/_3$ NPK+ $ZnNPs_{100}$; $^2/_3$ NPK+ $SiNPs_{50}$; $^2/_3$ NPK+ $SiNPs_{100}$; $^2/_3$ NPK+ $SiNPs_{200}$; and N_0:P_0:K_0. Results indicated that the grain yield (10.05 and 9.79 t ha^{-1}) and straw yield (13.68 and 12.45 t ha^{-1}) in the 2019 and 2020 seasons, respectively, as well as the yield attributes, chemical compositions in the plant, and milling characteristics, were significantly altered by the application of $^2/_3$ NPK+ Zn_{50}NPs without any significant difference in comparison to the $N_{165}P_{36}K_{60}$ treatment. Moreover, $^2/_3$ NPK+ P_{3000}NPs and $^2/_3$ NPK+ Si_{200}NPs recorded positive effects on all studied characteristics. The findings of this study will be useful for future investigations, including the use of nanofertilizers in rice.

Keywords: nanofertilizer; rice yield; nutrient uptake; foliar fertilization

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1. Introduction

Rice is one of the most important cereal crops and a staple food consumed in Egypt and all over the world. Improving rice cultivation is essential for guaranteeing food security since it gives farmers an income, reduces poverty, and provides a food source for the majority of the world's population [1]. High amounts of fertilizer, such as ammonium sulfate, urea, and nitrate or phosphate compounds, are unsafe [2]. Heavy use of mineral nitrogen, phosphorus, and potassium (NPK) fertilizers has become a major anthropogenic factor resulting in worldwide eutrophication problems in freshwater bodies and coastal ecosystems [3,4]. Farmers use a large amount of NPK fertilizers that is unavailable to plants because it is lost as run-off or leaching, and causes pollution under continuous irrigation conditions [5,6]. Nanofertilizers have been developed and have provided a new efficient alternative to normal regular fertilizers [7]. Meanwhile, nanotechnology increases the application efficiency of fertilizers and decreases pollution and the risks of chemical fertilization [8]. Nanoparticles may increase plant metabolism due to their distinctive physicochemical characteristics [9]. In addition, when compared to chemical fertilizers' requirements and cost, nanofertilizers are economically cheaper and are required in lesser amounts [5]. The use of nanoparticles in the growth of plants and for the control of plant diseases is a recent practice. In terms of nutrient availability for plants, the traditional methods of applying nanofertilizers to the soil have various shortcomings, including the likelihood of the plant diseases. The most effective method of dealing with nutrient shortages, reducing rice diseases, and improving crop yield and quality is therefore through foliar spray. This method also reduces environmental contamination and increases nutrient use efficiency via decreasing the amount of fertilizer applied to the soil [8,10,11]. Nanomaterials increase plant resistance to biotic and abiotic stress and diseases, whereas nanofertilizers improve overall plant health [7]. Nanomaterials can be used in a variety of ways, including antimicrobial agents that can directly reduce the virulence of diseases. They were particularly effective against the bacteria and fungi *Xanthomonas perforans*, *Fusarium oxysporum*, and *Phytophthora infestans*. Studies have demonstrated the potential of nanomaterials to inhibit pathogen infection and enhance plant growth and crop productivity at an adequate dose [10]. In contrast to other important micronutrients such as nitrogen, potassium, and phosphate, rice is a silicon-loving crop because it can absorb and accumulate substantial amounts of silicon to a greater level (up to 10%) of shoot dry weight [4]. By foliar application, SiO_2 NPs, in the right concentration range, could promote plant immunity to improve rice's resistance against the rice blast fungus. It might be a different method of preventing crop diseases, including Fusarium stalk rot (caused by *Fusarium graminearum*), rice blast (caused by *M. oryzae*), and bacterial leaf blight (*Xanthomonas oryzae pv. oryzae*) on rice [10]. Nanoparticles are defined based on the size at which their fundamental properties differ from those of the corresponding bulk material [12]. It is important to note that several nanonutrients can be used for plant nutrition by foliar application, including nano P, [13], nano zinc [14], and nano silicon [15]. If rock phosphate is used in nano form, the amount of phosphorus that is available to plants may be increased because the direct application of rock phosphate nanoparticles (PNPs) to crops may prevent phosphorus from being fixed in the soil; in addition, since there is no need for silicic acid, iron, or calcium in this process, phosphorus is more readily available to crop plants [16]. Zinc nanoparticles (ZnNPs) are one of the most widely used nanomaterials, extensively utilized in personal care products, paints, and also as anti-microbial agents [17,18]. The foliar application of silicon nanoparticles (SiNPs) shows positive effects on growth and yield, especially when higher concentrations are used. This treatment increases the epidermal cell-wall thickness of rice leaves [19]. The use of nanofertilizers, that move with the smallest conceivable particles, offers hope for increasing rice yield by finding solutions to issues that cannot be addressed in the traditional way. To reduce the heavy use of chemical inputs without sacrificing output and nutritional benefits, it would be highly beneficial if we used nanofertilizers for certain crops such as rice [20]. Foliar application, by which most new nanofertilizers may be administered, was and continues to be one of the most significant agro-technological tools. This farming method has the potential to be a useful tool for plant bio fortification [21,22]. Foliar fertilization is the practice of applying one or more necessary plant nutrients through foliar sprays or other methods to plant portions, in place of the fertilizers often applied through traditional soil applications. [23]. The goal of this study is to evaluate the influence of nanofertilizers as foliar applications combined with the basal treatment of mineral NPK on the Egyptian Giza 179 rice variety.

2. Materials and Methods

2.1. Field Experiment

At the experimental farm of the Rice Research and Training Centre (RRTC), Sakha Agricultural Research Station, Kafrelsheikh, Egypt (30°57′12′′ north latitude, 31°07′19′′ east longitude), a field experiment was carried out during two successive seasons in 2019 and 2020. At each site, representative soil samples were collected 0–30 cm below the soil's surface. After being thoroughly combined and powdered to fit through a 2 mm filter, samples were air-dried, this technique is based on a soil analysis method [24]. Soil physiochemical analysis of the experimental site during the 2019 and 2020 seasons showed that soil texture was clayey, organic matter 1.59 and 1.53, pH (1:2.5 water suspension) 8.12 and 8.18, Ec (ds m^{-1}) 2.55 and 2.25, available NH_4^+ (mg kg^{-1}) 14.15 and 13.70, available P (mg kg^{-1}) 11.92 and 12.00, available K (mg kg^{-1}) 375 and 380, available micronutrients (mg L^{-1}) Fe^{2+} (5.95 and 5.30), Mn^{2+} (3.30 and 3.10), Zn^{2+} (1.00 and 1.15), soluble anions (meq. L^{-1}) HCO^{3-} (17.80 and 17.00), Cl^- (17.20 and 16.90), SO_4^{2-} (3.12 and 2.90), soluble cations (Meq. L^{-1}) Ca^{2+} (9.41 and 8.25), Mg^{2+} (4.52 and 3.80), K^+ (1.48 and 1.22), Na^+ (12.40 and 13.05), respectively.

To speed up early germination, the Egyptian Giza 179 rice seeds were sown at a rate of 96 kg per hectare. Then, they were soaked in water for 24 h and incubated for 48 h to promote early germination. On 15 May of the two seasons, pre-germinated seeds were uniformly dispersed across the nursery. The permanent field was prepped by being twice through-plowed and then receiving a thorough wet leveling. After 30 days from the date of seeding, seedlings were carefully removed from the nursery and distributed among the plots. Seedlings were transplanted by hand into 12 m^2 subplots with a 20 × 20 cm spacing at a rate of 2–3 seedlings per hill. Plots were maintained submerged until two to three weeks before harvest. In the two seasons, barley was the previous crop. The conventional agricultural cultivation methods were recommended by RRTC, Sakha, Kafrelsheikh, Egypt. As the required dose, a mineral nitrogen (N) fertilizer in the form of urea (46.5% N) was administered at a rate of 165 kg N ha^{-1} to the Egyptian Giza 179 rice variety. Each plot received two doses of urea, with the first two-thirds of the amount serving as a basal application. The remaining one-third of the dosage was utilized as top-dressing 30 days after transplantation (DAT). At the time of final field preparation, a mineral phosphorus (P) fertilizer in the form of single super phosphate (SSP) with 15.5% P_2O_5 was added and thoroughly integrated into the soil as a basal treatment at the rate of 36 kg ha^{-1} as a recommended P dose for the Egyptian Giza 179 rice variety. At the time of the final land preparation, a mineral potassium (K) fertilizer in the form of potassium sulfate (50% K_2O) was added and carefully incorporated into the soil as a basal treatment at the rate of 60 kg ha^{-1} as a recommended K dose for the Egyptian Giza 179 rice variety.

Phosphorus nanoparticles (PNPs) in the form of hydroxyapatite $Ca_5(PO_4)_3$ OH nanoparticles were applied in a liquid solution of 1000, 3000, and 5000 mg L^{-1} concentrations ha^{-1}, respectively, and were used as a foliar application at the booting stage (25 days after transplanting DAT). Zinc nanoparticles (ZnNPs) in the form of zinc oxide (ZnO) nanoparticles were applied in a liquid solution of 25, 50, and 100 mg L^{-1} concentrations ha^{-1}, respectively, and were used as a foliar application at the booting stage. Silicon nanoparticles (SiNPs) in the form of silicon dioxide (SiO_2) nanoparticles were applied in a liquid solution of 50, 100, and 200 mg L^{-1} concentrations ha^{-1}, respectively, and were used as a foliar application at the booting stage. The particle sizes of nano phosphorus, nano zinc, and nano silicon ranged from 30 to 60, 10 to 30, and 20 to 30 nm, respectively, and had 99% purity. The solution was prepared by dispersing nanoparticles in deionized water in an ultrasonic water bath (300 W, 40 kHz) with magnetic stirring for 30 min [25].

Characterization of Nanoparticles

Based on their UV–Vis absorption peaks, the best NPs samples under various synthesis conditions were identified, and their particle size was validated by dynamic light scattering (DLS) analysis. Only the perfect NPs samples were submitted to additional characterizations including FT-IR, zeta potential, and TEM investigation. NPs' UV–Vis absorption peaks were measured with a UV–Vis spectrophotometer (JASCO, V-630, Portland, OR, USA) operating at room temperature and in the 200–800 nm scanning wavelength range. Before measurement, the samples were sonicated using the Alpha FT-IR spectrophotometer (Bruker, Billerica, Massachusetts, USA), which was outfitted with an ATR sample base plate Diamond. Utilizing FT-IR spectroscopy in the 400–4000 cm^{-1} wavenumber region, the composition of NPs was identified. Using the DLS method on a Malvern Zeta-sizer 2000

(Nano-ZS; Malvern Instruments, Malvern, UK) at 25 °C, the average size of NPs dispersed in deionized water was determined. Before each measurement, nanoparticles were suspended in deionized water using sonication. Dynamic light scattering (DLS) measurement of size and zeta potential (ζ-P) was calculated using the Laser Doppler Velocimetry (LDV) technique on a Malvern Zetasizer 2000 (Nano-ZS; Malvern Instruments, Malvern, UK). To evaluate the sample's elementary composition, an energy dispersive analysis by X-ray (EDAX) occurred using a JEOL JSM-6100 scanning electron microscope (JEOL, Ltd., Tokyo, Japan) using the OXFORD X-ray Microanalysis software (CA, USA). Synthesis and characterization of NPs were described at Nanotechnology and Advanced Materials Central Laboratory (NAMCL), Agricultural Research Center (ARC), Ministry of Agriculture and Land Reclamation, Egypt.

To characterize the size distribution and morphology of the synthesized phosphorus, zinc, and silicon nanoparticles, transmission electron microscopy (TEM) was used. Using a JEOL JEM-2100 electronic microscope (JEOL, Ltd., Tokyo, Japan) with a voltage gradient of 100 kV, the texture of nanoparticles was investigated by TEM analysis (Figure 1) [26].

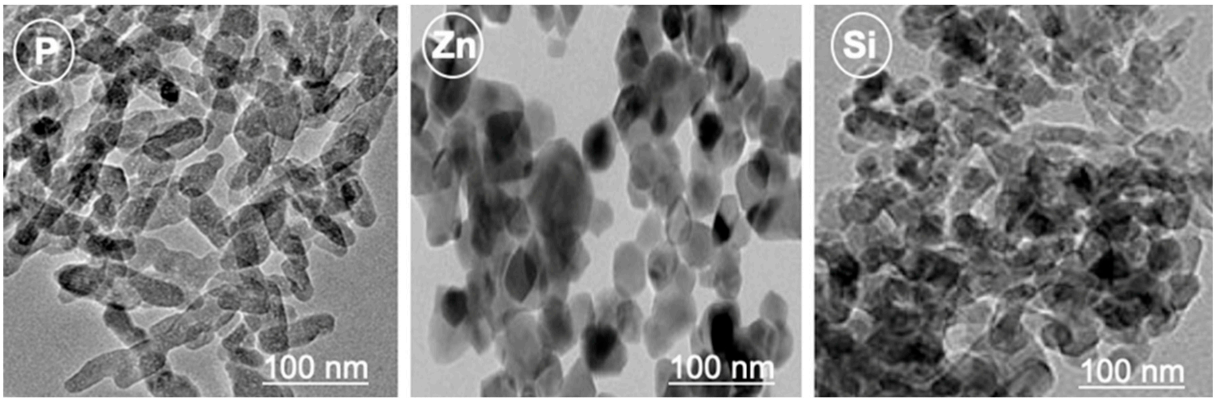

Figure 1. Transmission electron microscopy (TEM) of phosphorus zinc and silicon nanoparticles.

2.2. Experiment Treatments

In the two seasons, 2019 and 2020, the experiments were conducted utilizing a Randomized Complete Block Design with four replications; to evaluate the response of rice to the foliar application of phosphorus, zinc and silicon nanoparticles, which included: T_1: basal application of 165 Urea: 36 P_2O_5: 60 K_2O kg ha^{-1} NPK as the recommended dose (N_{165}:P_{36}:K_{60}),T_2: basal application of 110 Urea: 24 P_2O_5: 40 K_2O kg ha^{-1} NPK ($N_{110}P_{24}K_{40}$) or $^2/_3$ NPK, T_3: $^2/_3$ NPK + foliar application of 1000 mg L^{-1} of nano phosphorus ($PNPs_{1000}$), T_4: $^2/_3$ NPK + foliar application of 3000 mg L^{-1} of nano phosphorus ($PNPs_{3000}$), T_5: $^2/_3$ NPK + foliar application of 5000 mg L^{-1} of nano phosphorus ($PNPs_{5000}$), T_6: $^2/_3$ NPK + foliar application of 25 mg L^{-1} of nano zinc ($ZnNPs_{25}$), T_7: $^2/_3$ NPK + foliar application of 50 mg L^{-1} of nano zinc ($ZnNPs_{50}$), T_8: $^2/_3$ NPK + foliar application of 100 mg L^{-1} of nano zinc ($ZnNPs_{100}$), T_9: $^2/_3$ NPK + foliar application of 50 mg L^{-1} of nano silicon ($SiNPs_{50}$), T_{10}: $^2/_3$ NPK + foliar application of 100 mg L^{-1} of nano silicon ($SiNPs_{100}$), T_{11}: $^2/_3$ NPK + foliar application of 200 mg L^{-1} of nano silicon ($SiNPs_{200}$), T_{12}: zero NPK fertilizers, N_0:P_0:K_0 (control).

2.3. Studied Characteristics

To estimate the number of panicles m^{-2} at harvest, five hills from each plot were randomly selected. To calculate the filled grain weight (g), panicle length (cm), number of grains panicle^{-1}, 1000-grains weight (g), and percentage of filled grains during harvest, the panicles of ten hills for each plot were taken. Each plot's inner 9 m^2 was manually picked and dried at a moisture content of 14%, and the weight of the grain and straw produced was recorded. The dried plants were then mechanically threshed to calculate grain yield productivity per t ha^{-1}.

After harvest, dried grains and straw samples were ground into a fine powder, to determine nitrogen content (N%) in the grain and straw using the Orange–G Dye method [27].

Dried samples of the grain and straw after harvest were ground to powder and digested [28], to estimate:

- Phosphorus content (P%) in the grains and straw was extracted as described by [29] and measured by spectrophotometer (Spectrophotometer UV-Vis Biochrom Libra S-12, Cambridge, England), absorbance measurements were performed at wavelengths ranging from 800to 900 nm) using the ascorbic acid method [30].
- Potassium content (K%) in the grains and straw was determined using the Flame photometer method [31].
- Zinc content (Zn%) in the grains and straw was determined by the atomic absorption spectrophotometer, Model 153 [32].
- Silicon content (Si%) in the grains and straw [33].

Then, nitrogen, phosphorus, potassium, zinc, and silicon uptake (Kg ha^{-1}) were determined as follows:

$$\text{Element (N, P, K, Si, and Zn)uptake} \left(Kg\ ha^{-1}\right) = \text{Element \% in grain or straw} \times \text{dry weight of grain or straw}$$

Protein content (%), was estimated [34], as follows:

$$\text{Protein\%} = \text{N \% in grain} \times 5.95$$

At the grain quality Lab., RRTC, Sakha, Egypt, about 150 g of fresh, rough rice grains were taken at random after harvest and well mixed, cleaned, and analyzed for the Milling characters; hulling%, milling%, and broken rice% [35] as follows:

$$\text{Hulling \%} = \frac{\text{Brown rice weight (g)}}{\text{Rough rice weight (g)}} \times 100$$

$$\text{Milling \%} = \frac{\text{Milled rice weight (g)}}{\text{Rough rice weight (g)}} \times 100$$

$$\text{Broken rice \%} = \frac{\text{Weight of broken rice (g)}}{\text{Milled rice weight (g)}} \times 100$$

2.4. Statistical Analyses

Using a Randomized Complete Block Design, ANOVA was run on the data [36]. The variations between the treatments were compared using Duncan's Multiple Range Test ($p < 0.05$) [37]. The statistical package MSTAT-C [38,39] was applied.

3. Results

3.1. Grain yield Attributes

Table 1 shows the number of panicles m^{-2} at harvest, filled grains panicle^{-1}, and panicle length of the Egyptian Giza 179 rice variety as influenced by foliar application with phosphorus, zinc, and silicon nanoparticles and their concentrations with mineral NPK fertilizers in the 2019 and 2020 seasons. The number of panicles m^{-2} at harvest, filled grains weight panicle^{-1}, and panicle length significantly increased by the application of two-thirds of the recommended dose of mineral NPK as a basal application + foliar application of nano zinc fertilization in concentration 50 mg L^{-1} at the booting stage ($^2/_3$ NPK+ Zn_{50} NPs) or $N_{165}P_{36}K_{60}$ (165 Urea: 36 P_2O_5: 60 K_2O kg ha^{-1}).

Table 1. Effect of foliar application of P, Zn, and Si nanoparticles in combination with mineral NPK fertilization on a number of panicles m^{-2} at harvest, filled grains $panicle^{-1}$, and panicle length of Egyptian Giza 179 rice variety in 2019 and 2020 seasons.

Treatments	No. of Panicles m^{-2}		Filled Grains wt. $Panicle^{-1}$ (g)		Panicle Length (cm)	
	2019	2020	2019	2020	2019	2020
N_{165}:P_{36}:K_{60} (NPK)	458.3 b	458.3 b	2.03 a	2.33 a	19.33 ab	19.17
N_{110}:P_{24}:K_{40} ($^2/_3$ NPK)	408.3 bc	416.7 h	1.70 f	1.88 ef	17.33 bc	17.67
$^2/_3$ NPK + $PNPs_{1000}$	441.7 bc	433.3 e	1.83 c-e	1.92 d-f	18.67 a-c	19.00
$^2/_3$ NPK + $PNPs_{3000}$	455.0 b	458.3 b	1.95 a-c	2.13 b	18.33 a-c	18.33
$^2/_3$ NPK + $PNPs_{5000}$	441.7 bc	425.0 f	1.88 b-d	1.97 c-e	17.67 bc	18.67
$^2/_3$ NPK + $ZnNPs_{25}$	450.0 b	433.3 e	1.78 d-f	1.83 fg	18.67 a-c	18.33
$^2/_3$ NPK + $ZnNPs_{50}$	541.7 a	466.7 a	2.00 ab	2.27 ab	20.33 a	17.67
$^2/_3$ NPK + $ZnNPs_{100}$	425.0 bc	433.3 e	1.72 ef	1.85 fg	17.33 bc	18.33
$^2/_3$ NPK + $SiNPs_{50}$	441.7 bc	418.3 g	1.77 d-f	1.92 d-f	18.33 a-c	18.00
$^2/_3$ NPK + $SiNPs_{100}$	450.0 b	441.7 d	1.92 a-c	2.00 cd	18.67 a-c	17.67
$^2/_3$ NPK + $SiNPs_{200}$	450.0 b	450.0 c	1.93 a-c	2.03 c	18.00 bc	18.67
N_0:P_0:K_0 (0 NPK)	391.7 c	400.0 i	1.52 g	1.78 g	17.00 c	17.33
F. test	**	**	**	**	**	NS

Columns with different lowercase letters indicate a significant difference at $p \leq 0.05$, ** a significant effect at $p \leq 0.01$, and NS no significant effect at $p \leq 0.05$, respectively. The means of each factor designated at $p \leq 0.05$ level using Duncan's Multiple Range Test. NPK = Mineral NPK; PNPs = Phosphorus nanoparticles; ZnNPs = Zinc nanoparticles; SiNPs = Silicon nanoparticles.

Different concentrations of nanoparticles with mineral fertilizers had significant effects on yield attributes of the Egyptian Giza 179 rice variety such as the number of grains $panicle^{-1}$, percentage of filled grains, and 1000-grains weight in the 2019 and 2020 seasons as affected by the foliar application of phosphorus, zinc, and silicon nanoparticles and their concentrations with mineral NPK fertilizers. Table 2 clarifies the number of grains $panicle^{-1}$ and percentage of filled grains significantly increased by the application of $^2/_3$ NPK + Zn_{50}NPs as two-thirds of the recommended dose of mineral NPK in the basal application + foliar application of nano zinc fertilizer in concentration 50 mg L^{-1} at the booting stage, with no significant differences with $N_{165}P_{36}K_{60}$ (165 Urea: 36 P_2O_5: 60 K_2O kg ha^{-1}) as the recommended dose. The 1000-grains weight significantly enhanced without any mineral NPK fertilization or N_{110}:P_{24}:K_{40} ($^2/_3$ NPK), then $N_{165}P_{36}K_{60}$.

3.2. Chemical Compositions

3.2.1. Nitrogen Uptake

Figure 2 shows the impact of the foliar application of phosphorus, zinc, and silicon nanoparticles, along with its concentrations with mineral NPK fertilizers, on nitrogen uptake (N uptake) in the grain and straw of the Egyptian Giza 179 rice variety during the 2019 and 2020 growing seasons. N uptake in the grain and straw was significantly raised by applying $^2/_3$ NPK + Zn_{50}NPs as two-thirds of the full dose of mineral NPK in the basal application + foliar application of nano zinc fertilizer in concentration 50 mg L^{-1} at the booting stage, or with $N_{165}P_{36}K_{60}$ (165 Urea: 36 P_2O_5: 60 K_2O kg ha^{-1}). Then, applying $^2/_3$ NPK + Si_{200}NPs (200 mg L^{-1} of nano silicon) or $^2/_3$ NPK + P_{5000}NPs (5000 mg L^{-1} of nano phosphorus) also enhanced N uptake in the grain and straw of the Egyptian Giza 179 rice variety.

Table 2. Effect of foliar application of P, Zn, and Si nanoparticles in combination with mineral NPK fertilization on a number of grains panicle^{-1}, filled grains percentage, and 1000-grains weight of Egyptian Giza 179 rice variety in 2019 and 2020 seasons.

Treatments	No. of Grains Panicle^{-1}		Filled Grains (%)		1000-Grains wt.(g)	
	2019	2020	2019	2020	2019	2020
N_{165}:P_{36}:K_{60} (NPK)	81.67 a	85.00 a	86.33 ab	86.33 ab	25.00 a–c	25.00 ab
N_{110}:P_{24}:K_{40} ($^2/_3$ NPK)	70.00 cd	71.67 d	82.00 bc	81.67 bc	26.33 a	26.00 a
$^2/_3$ NPK + $PNPs_{1000}$	71.67 cd	75.00 cd	83.00 bc	82.67 a–c	24.33 b–d	25.00 ab
$^2/_3$ NPK + $PNPs_{3000}$	76.67 a–c	81.67 ab	84.33 a-c	84.00 a–c	23.00 c–e	23.00 ab
$^2/_3$ NPK + $PNPs_{5000}$	71.67 cd	73.33 cd	85.67 a-c	85.00 a–c	23.00 c–e	23.00 ab
$^2/_3$ NPK + $ZnNPs_{25}$	70.00 cd	73.33 cd	85.33 a-c	84.67 a–c	22.67 de	22.33 b
$^2/_3$ NPK + $ZnNPs_{50}$	80.00 ab	81.67 ab	88.00 a	87.00 a	21.33 e	22.33 b
$^2/_3$ NPK + $ZnNPs_{100}$	71.67 cd	71.67 d	83.00 bc	83.67 a–c	24.33 b–d	25.00 ab
$^2/_3$ NPK + $SiNPs_{50}$	71.67 cd	71.67 d	83.33 a–c	84.00 a–c	23.33 c–e	24.00 ab
$^2/_3$ NPK + $SiNPs_{100}$	73.33 b–d	71.67 d	85.00 a–c	84.67 a–c	23.67 cd	24.33 ab
$^2/_3$ NPK + $SiNPs_{200}$	75.00 a–d	78.33 bc	85.67 a–c	86.00 ab	22.67 de	22.00 b
N_0:P_0:K_0 (0 NPK)	68.33 d	70.00 d	81.33 c	80.67 c	25.67 ab	25.67 a
F. test	**	**	**	**	**	*

Columns with different lowercase letters indicate a significant difference at $p \leq 0.05$., *, and **, a significant effect at $p \leq 0.05$ and $p \leq 0.01$, respectively. The means of each factor designated at $p \leq 0.05$ level using Duncan's Multiple Range Test. NPK = Mineral NPK; PNPs = Phosphorus nanoparticles; ZnNPs = Zinc nanoparticles; and SiNPs = Silicon nanoparticles.

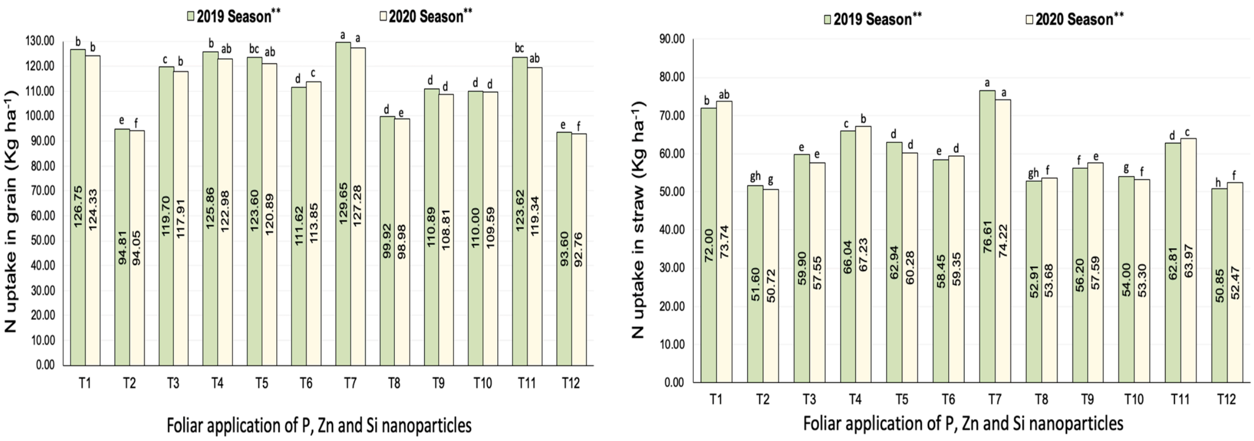

Figure 2. Effect of foliar application of P, Zn, and Si nanoparticles in combination with mineral NPK fertilization on N uptake in grain and straw of Egyptian Giza 179 rice variety in 2019 and 2020 seasons. A significant difference at $p \leq 0.05$ ** is listed by different lowercase letters above the bars, a significant effect at $p \leq 0.01$. The means of each factor designated at $p \leq 0.05$ level using Duncan's Multiple Range Test. T_1: basal application of 165 Urea: 36 P_2O_5: 60 K_2O kg ha^{-1} NPK as the recommended dose (N_{165}:P_{36}:K_{60}); T_2: basal application of 110 Urea: 24 P_2O_5: 40 K_2O kg ha^{-1} NPK ($N_{110}P_{24}K_{40}$) or $^2/_3$ NPK; T_3: $^2/_3$ NPK + foliar application of 1000 mg L^{-1} of nano phosphorus ($PNPs_{1000}$); T_4: $^2/_3$ NPK + foliar application of 3000 mg L^{-1} of nano phosphorus ($PNPs_{3000}$); T_5: $^2/_3$ NPK + foliar application of 5000 mg L^{-1} of nano phosphorus ($PNPs_{5000}$); T_6: $^2/_3$ NPK + foliar application of 25 mg L^{-1} of nano zinc ($ZnNPs_{25}$); T_7: $^2/_3$ NPK + foliar application of 50 mg L^{-1} of nano zinc ($ZnNPs_{50}$); T_8: $^2/_3$ NPK + foliar application of 100 mg L^{-1} of nano zinc ($ZnNPs_{100}$); T_9: $^2/_3$ NPK + foliar application of 50 mg L^{-1} of nano silicon ($SiNPs_{50}$); T_{10}: $^2/_3$ NPK + foliar application of 100 mg L^{-1} of nano silicon ($SiNPs_{100}$); T_{11}: $^2/_3$ NPK + foliar application of 200 mg L^{-1} of nano silicon ($SiNPs_{200}$); T_{12}: zero NPK fertilizers (N_0:P_0:K_0) or control.

3.2.2. Phosphorus Uptake

The effects of the foliar application of phosphorus, zinc, and silicon nanoparticles, and their concentrations along with mineral NPK fertilizers, on phosphorus uptake (P uptake) in the grain and straw of the Egyptian Giza 179 rice variety in the 2019 and 2020 seasons are displayed in Figure 3. P uptake in the grain and straw was significantly increased by applying $^2/_3$ NPK + Zn_{50}NPs in two-thirds of the ideal dose of mineral NPK in the basal application + foliar sprays of nano zinc fertilization in concentration 50 mg L^{-1} at the booting stage, followed by $N_{165}P_{36}K_{60}$ (165 Urea: 36 P_2O_5: 60 K_2O kg ha^{-1}) without significant differences with $^2/_3$ NPK + P_{3000}NPs (3000 mg L^{-1} of nano phosphorus). Then, applying $^2/_3$ NPK + Si_{200}NPs (200 mg L^{-1} of nano silicon), or $^2/_3$ NPK + P_{1000}NPs (1000 mg L^{-1} of nano phosphorus), or $^2/_3$ NPK + P_{5000}NPs (5000 mg L^{-1} of nano phosphorus) also improved P uptake in the grain and straw in the two seasons.

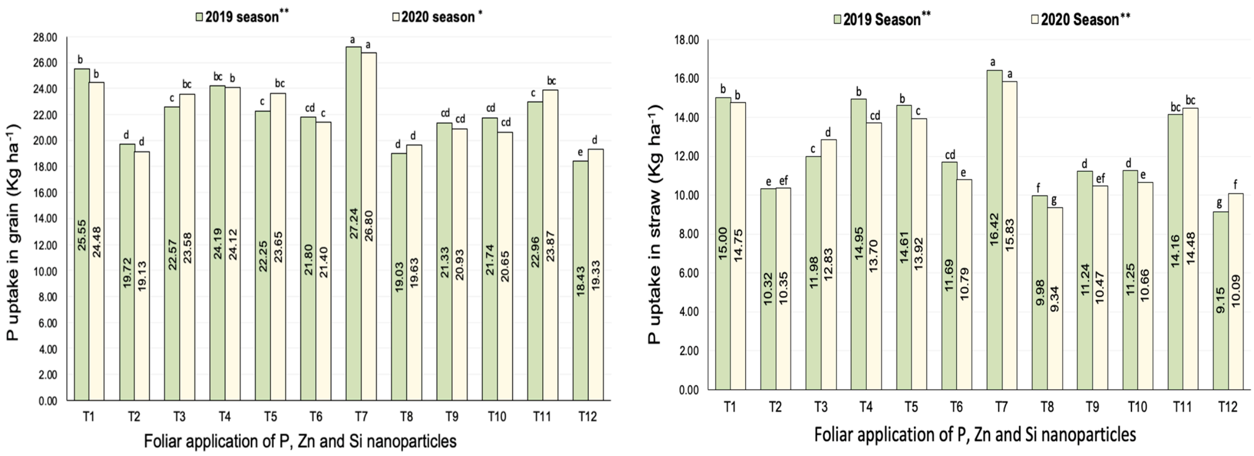

Figure 3. Effect of foliar application of P, Zn, and Si nanoparticles in combination with mineral NPK fertilization on phosphorus uptake in grain and straw of Egyptian Giza 179 rice variety in 2019 and 2020 seasons. A significant difference at $p \leq 0.05$ ** is listed by different lowercase letters above the bars, *, and **, a significant effect at $p \leq 0.05$ and $p \leq 0.01$, respectively. The means of each factor designated at $p \leq 0.05$ level using Duncan's Multiple Range Test. T_1: basal application of 165 Urea: 36 P_2O_5: 60 K_2O kg ha^{-1} NPK as the recommended dose (N_{165}:P_{36}:K_{60}); T_2: basal application of 110 Urea: 24 P_2O_5: 40 K_2O kg ha^{-1} NPK ($N_{110}P_{24}K_{40}$) or $^2/_3$ NPK; T_3: $^2/_3$ NPK + foliar application of 1000 mg L^{-1} of nano phosphorus ($PNPs_{1000}$); T_4: $^2/_3$ NPK + foliar application of 3000 mg L^{-1} of nano phosphorus ($PNPs_{3000}$); T_5: $^2/_3$ NPK + foliar application of 5000 mg L^{-1} of nano phosphorus ($PNPs_{5000}$); T_6: $^2/_3$ NPK + foliar application of 25 mg L^{-1} of nano zinc ($ZnNPs_{25}$); T_7: $^2/_3$ NPK + foliar application of 50 mg L^{-1} of nano zinc ($ZnNPs_{50}$); T_8: $^2/_3$ NPK + foliar application of 100 mg L^{-1} of nano zinc ($ZnNPs_{100}$); T_9: $^2/_3$ NPK + foliar application of 50 mg L^{-1} of nano silicon ($SiNPs_{50}$); T_{10}: $^2/_3$ NPK + foliar application of 100 mg L^{-1} of nano silicon ($SiNPs_{100}$); T_{11}: $^2/_3$ NPK + foliar application of 200 mg L^{-1} of nano silicon ($SiNPs_{200}$); T_{12}: zero NPK fertilizers (N_0:P_0:K_0) or control.

3.2.3. Potassium Uptake

The effects of foliar application of phosphorus, zinc, and silicon nanoparticles, as well as their concentrations with mineral NPK fertilizers, on potassium uptake in the grain and straw of the Egyptian Giza 179 rice variety in the 2019 and 2020 seasons, are presented in Figure 4. The potassium uptake in grain and straw was significantly increased by applying $^2/_3$ NPK + Zn_{50}NPs as two-thirds of the recommended dose of mineral NPK in the basal application + foliar sprays of nano zinc fertilizer in concentration 50 mg L^{-1} at the booting stage, followed by $N_{165}P_{36}K_{60}$ (165 Urea: 36 P_2O_5: 60 K_2O kg ha^{-1}) as the recommended NPK dose for the Egyptian rice variety without significant differences with $^2/_3$ NPK + P_{3000}NPs (3000 mg L^{-1} of nano phosphorus). Then, applying $^2/_3$ NPK + Si_{200}NPs (200 mg L^{-1} of nano silicon) also increased the P uptake in the grain and straw. Zero NPK recorded the lowest values of K uptake in the two seasons.

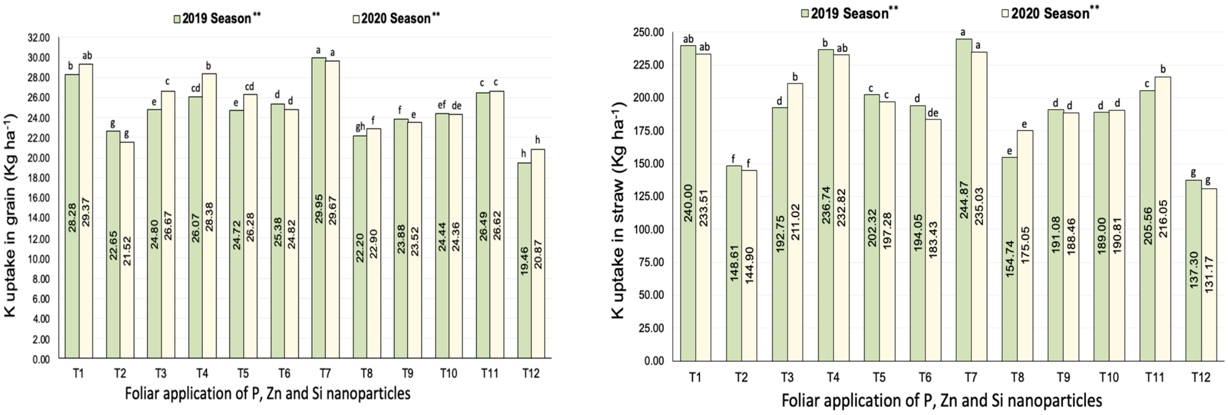

Figure 4. Effect of foliar application of P, Zn, and Si nanoparticles in combination with mineral NPK fertilization on potassium uptake in grain and straw of Egyptian Giza 179 rice variety in 2019 and 2020 seasons. A significant difference at $p \leq 0.05$ ** is listed by different lowercase letters above the bars, ** a significant effect at $p \leq 0.01$. The means of each factor designated at $p \leq 0.05$ level using Duncan's Multiple Range Test. T_1: basal application of 165 Urea: 36 P_2O_5: 60 K_2O kg ha^{-1} NPK as the recommended dose (N_{165}:P_{36}:K_{60}), T_2: basal application of 110 Urea: 24 P_2O_5: 40 K_2O kg ha^{-1} NPK ($N_{110}P_{24}K_{40}$) or $^2/_3$ NPK, T_3: $^2/_3$ NPK + foliar application of 1000 mg L^{-1} of nano phosphorus ($PNPs_{1000}$), T_4: $^2/_3$ NPK + foliar application of 3000 mg L^{-1} of nano phosphorus ($PNPs_{3000}$), T_5: $^2/_3$ NPK + foliar application of 5000 mg L^{-1} of nano phosphorus ($PNPs_{5000}$), T_6: $^2/_3$ NPK + foliar application of 25 mg L^{-1} of nano zinc ($ZnNPs_{25}$), T_7: $^2/_3$ NPK + foliar application of 50 mg L^{-1} of nano zinc ($ZnNPs_{50}$), T_8: $^2/_3$ NPK + foliar application of 100 mg L^{-1} of nano zinc ($ZnNPs_{100}$), T_9: $^2/_3$ NPK + foliar application of 50 mg L^{-1} of nano silicon ($SiNPs_{50}$), T_{10}: $^2/_3$ NPK + foliar application of 100 mg L^{-1} of nano silicon ($SiNPs_{100}$), T_{11}: $^2/_3$ NPK + foliar application of 200 mg L^{-1} of nano silicon ($SiNPs_{200}$), T_{12}: zero NPK fertilizers (N_0:P_0:K_0) or control.

3.2.4. Zinc Uptake

The effects of foliar application of phosphorus, zinc, and silicon nanoparticles, and its concentrations with mineral NPK fertilizers, on zinc (Zn) uptake in the grain and straw of the Egyptian Giza 179 rice variety in the 2019 and 2020 seasons are presented in Figure 5. Zn uptake in the grain and straw was significantly boosted by applying $^2/_3$ NPK + Zn_{50}NPs as two-thirds of the recommended dose of mineral NPK in the basal application form + foliar sprays of nano zinc fertilizer in concentration 50 mg L^{-1} at the booting stage, followed by $N_{165}P_{36}K_{60}$ (165 Urea: 36 P_2O_5: 60 K_2O kg ha^{-1}) without significant differences with $^2/_3$ NPK + P_{3000}NPs (3000 mg L^{-1} of nano phosphorus) or $^2/_3$ NPK + P_{5000}NPs (5000 mg L^{-1} of nano P). Zero NPK recorded the lowest values of Zn uptake in the two seasons.

3.2.5. Silicon Uptake

The foliar application of phosphorus, zinc, and silicon nanoparticles, and their concentrations with mineral NPK fertilizers influenced silicon (Si) uptake in the grain and straw of the Egyptian Giza 179 rice variety in the 2019 and 2020 seasons and are presented in Figure 6. Si uptake in the grain and straw was seriously improved by applying $^2/_3$ NPK + Zn_{50}NPs as two-thirds of the recommended dose of mineral NPK in the basal application form + foliar sprays of nano zinc fertilizer in concentration 50 mg L^{-1} at the booting stage, followed by $N_{165}P_{36}K_{60}$ (165 Urea: 36 P_2O_5: 60 K_2O kg ha^{-1}) with no differences with $^2/_3$ NPK + P_{3000}NPs (3000 mg L^{-1} of nano phosphorus). Then, applying $^2/_3$ NPK + Si_{200}NPs (200 mg L^{-1} of nano silicon) or $^2/_3$ NPK + P_{5000}NPs (5000 mg L^{-1} of nano phosphorus) also increased the Si uptake in the grain and straw. Zero NPK recorded the lowest values of Si uptake in the 2019 and 2020 seasons.

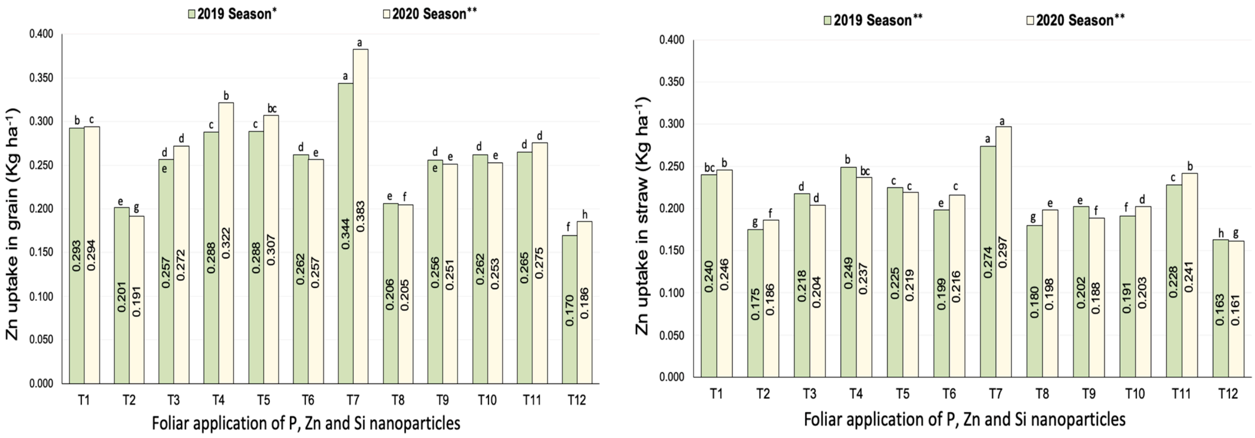

Figure 5. Effect of foliar application of P, Zn, and Si nanoparticles in combination with mineral NPK fertilization on zinc uptake in grain and straw of Egyptian Giza 179 rice variety in 2019 and 2020 seasons. A significant difference at $p \leq 0.05$ ** is listed by different lowercase letters above the bars, *, and **, a significant effect at $p \leq 0.05$ and $p \leq 0.01$, respectively. The means of each factor designated at $p \leq 0.05$ level using Duncan's Multiple Range Test. T_1: basal application of 165 Urea: 36 P_2O_5: 60 K_2O kg ha^{-1} NPK as the recommended dose (N_{165}:P_{36}:K_{60}); T_2: basal application of 110 Urea: 24 P_2O_5: 40 K_2O kg ha^{-1} NPK ($N_{110}P_{24}K_{40}$) or $^2/_3$ NPK; T_3: $^2/_3$ NPK + foliar application of 1000 mg L^{-1} of nano phosphorus ($PNPs_{1000}$); T_4: $^2/_3$ NPK + foliar application of 3000 mg L^{-1} of nano phosphorus ($PNPs_{3000}$); T_5: $^2/_3$ NPK + foliar application of 5000 mg L^{-1} of nano phosphorus ($PNPs_{5000}$); T_6: $^2/_3$ NPK + foliar application of 25 mg L^{-1} of nano zinc ($ZnNPs_{25}$); T_7: $^2/_3$ NPK + foliar application of 50 mg L^{-1} of nano zinc ($ZnNPs_{50}$); T_8: $^2/_3$ NPK + foliar application of 100 mg L^{-1} of nano zinc ($ZnNPs_{100}$); T_9: $^2/_3$ NPK + foliar application of 50 mg L^{-1} of nano silicon ($SiNPs_{50}$); T_{10}: $^2/_3$ NPK + foliar application of 100 mg L^{-1} of nano silicon ($SiNPs_{100}$); T_{11}: $^2/_3$ NPK + foliar application of 200 mg L^{-1} of nano silicon ($SiNPs_{200}$); T_{12}: zero NPK fertilizers (N_0:P_0:K_0) or control.

3.3. Grain and Straw Yields

Foliar application of phosphorus, zinc, and silicon nanoparticles and their concentrations with mineral NPK fertilizers affected the grain and straw yields of the Egyptian Giza 179 rice variety in the 2019 and 2020 seasons. Figure 7 showed that the grain and straw yields were considerably elevated by the application of $^2/_3$ NPK in basal application + Zn_{50}NPs in the foliar application of nano zinc fertilizer with concentration 50 mg L^{-1}) at the booting stage with no substantial differences with $N_{165}P_{36}K_{60}$ (165 Urea: 36 P_2O_5: 60 K_2O kg ha^{-1}) or $^2/_3$ NPK + P_{3000}NPs (3000 mg L^{-1} of nano phosphorus). In both seasons, zero NPK generated low grain and straw yields.

Table 3 shows the impact of foliar application of phosphorus, zinc, and silicon nanoparticles and its concentrations along with mineral NPK fertilizers in the 2019 and 2020 seasons on the grain quality properties of the Egyptian Giza 179 rice variety. Hulling%, milling%, and protein content in grain significantly increased by the application of $^2/_3$ mineral NPK + Zn_{50}NPs foliar application of nano zinc fertilizer in concentration 50 mg L^{-1} at the booting stage with no significant differences with $N_{165}P_{36}K_{60}$ (165 Urea: 36 P_2O_5: 60 K_2O kg ha^{-1}). Broken rice increased with zero NPK, hulling%, milling%, and protein content in grain recorded the lowest values with N_0:P_0:K_0 in the 2019 and 2020 seasons.

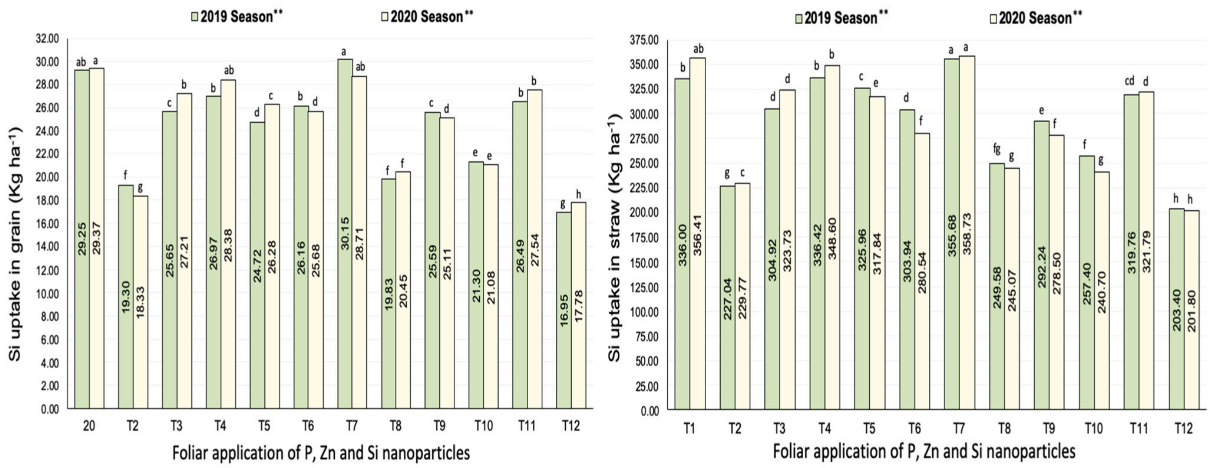

Figure 6. Effect of foliar application of P, Zn, and Si nanoparticles in combination with mineral NPK fertilization on silicon uptake in grain and straw of Egyptian Giza 179 rice variety in 2019 and 2020 seasons. A significant difference at $p \leq 0.05$ ** is listed by different lowercase letters above the bars, ** a significant effect at $p \leq 0.01$. The means of each factor designated at $p \leq 0.05$ level using Duncan's Multiple Range Test. T_1: basal application of 165 Urea: 36 P_2O_5: 60 K_2O kg ha^{-1} NPK as the recommended dose (N_{165}:P_{36}:K_{60}); T_2: basal application of 110 Urea: 24 P_2O_5: 40 K_2O kg ha^{-1} NPK ($N_{110}P_{24}K_{40}$) or $^2/_3$ NPK; T_3: $^2/_3$ NPK + foliar application of 1000 mg L^{-1} of nano phosphorus ($PNPs_{1000}$); T_4: $^2/_3$ NPK + foliar application of 3000 mg L^{-1} of nano phosphorus ($PNPs_{3000}$); T_5: $^2/_3$ NPK + foliar application of 5000 mg L^{-1} of nano phosphorus ($PNPs_{5000}$); T_6: $^2/_3$ NPK + foliar application of 25 mg L^{-1} of nano zinc ($ZnNPs_{25}$); T_7: $^2/_3$ NPK + foliar application of 50 mg L^{-1} of nano zinc ($ZnNPs_{50}$); T_8: $^2/_3$ NPK + foliar application of 100 mg L^{-1} of nano zinc ($ZnNPs_{100}$); T_9: $^2/_3$ NPK + foliar application of 50 mg L^{-1} of nano silicon ($SiNPs_{50}$); T_{10}: $^2/_3$ NPK + foliar application of 100 mg L^{-1} of nano silicon ($SiNPs_{100}$); T_{11}: $^2/_3$ NPK + foliar application of 200 mg L^{-1} of nano silicon ($SiNPs_{200}$); T_{12}: zero NPK fertilizers (N_0:P_0:K_0) or control.

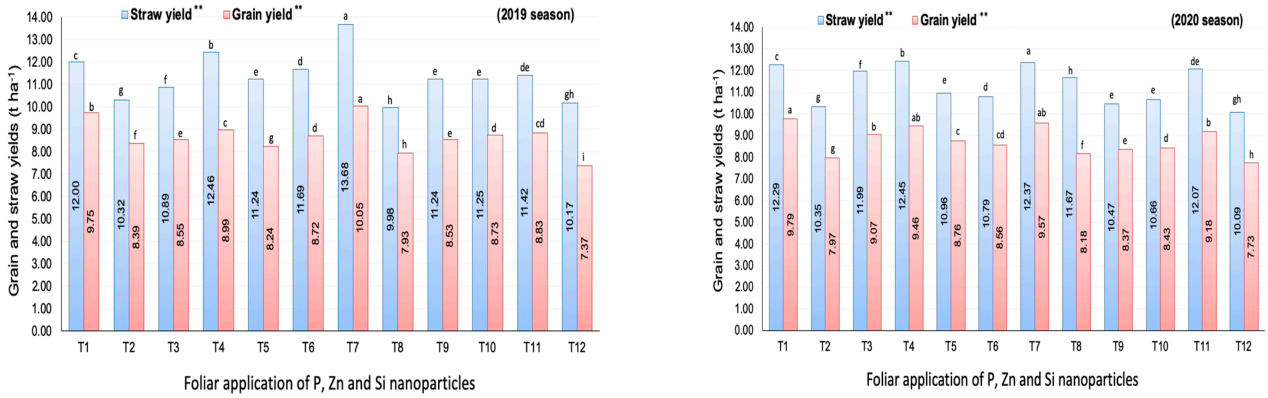

Figure 7. Effect of foliar application of P, Zn, and Si nanoparticles in combination with mineral NPK fertilization on grain and straw yields of Egyptian Giza 179 rice variety in 2019 and 2020 seasons. A significant difference at $p \leq 0.05$ ** is listed by different lowercase letters above the bars, ** a significant effect at $p \leq 0.01$. The means of each factor designated at $p \leq 0.05$ level using Duncan's Multiple Range Test. T1: basal application of 165 Urea: 36 P2O5: 60 K2O kg ha−1 NPK as the recommended dose (N165:P36:K60); T2: basal application of 110 Urea: 24 P2O5: 40 K2O kg ha−1 NPK

(N110P24K40) or 2/3 NPK; T3: 2/3 NPK + foliar application of 1000 mg L−1 of nano phosphorus (PNPs1000); T4: 2/3 NPK + foliar application of 3000 mg L−1 of nano phosphorus (PNPs3000); T5: 2/3 NPK + foliar application of 5000 mg L−1 of nano phosphorus (PNPs5000); T6: 2/3 NPK + foliar application of 25 mg L−1 of nano zinc (ZnNPs25); T7: 2/3 NPK + foliar application of 50 mg L−1 of nano zinc (ZnNPs50); T8: 2/3 NPK + foliar application of 100 mg L−1 of nano zinc (ZnNPs100); T9: 2/3 NPK + foliar application of 50 mg L−1 of nano silicon (SiNPs50); T10: 2/3 NPK + foliar application of 100 mg L−1 of nano silicon (SiNPs100); T11: 2/3 NPK + foliar application of 200 mg L−1 of nano silicon (SiNPs200); T12: zero NPK fertilizers (N0:P0:K0) or control.

Table 3. Effect of foliar application of P, Zn, and Si nanoparticles in combination with mineral NPK fertilization on hulling percentage, milling percentage, broken rice percentage, and protein content in grain of Egyptian Giza 179 rice variety in 2019 and 2020 seasons.

Treatments	Hulling (%)		Milling (%)		Broken Rice (%)		Protein Content (%)	
	2019	2020	2019	2020	2019	2020	2019	2020
N_{165}:P_{36}:K_{60} (NPK)	79.80 b	78.68 b	71.00 b	71.02 ab	33.96 gh	33.42 d	8.855 ab	8.614 ab
N_{110}:P_{24}:K_{40} ($^2/_3$ NPK)	75.70 g	75.14 fg	66.48 g	66.23 e	35.63 c	35.96 ab	6.724 d	7.021 e
$^2/_3$ NPK + $PNPs_{1000}$	76.31 f	76.53 e	69.27 e	69.49 c	33.82 h	34.80 c	7.735 c	7.557 c
$^2/_3$ NPK + $PNPs_{3000}$	78.99 c	78.43 bc	70.80 bc	70.83 ab	34.21 fg	33.73 d	8.110 bc	7.735 bc
$^2/_3$ NPK + $PNPs_{5000}$	76.50 f	76.37 e	69.07 e	69.90 bc	34.99 d	35.13 c	8.330 b	7.431 cd
$^2/_3$ NPK + $ZnNPs_{25}$	77.18 e	76.92 de	69.97 d	69.52 c	35.44 c	34.87 c	7.616 c	7.514 c
$^2/_3$ NPK + $ZnNPs_{50}$	80.56 a	79.83 a	71.70 a	71.15 a	34.56 ef	34.10 d	8.925 a	8.511 a
$^2/_3$ NPK + $ZnNPs_{100}$	75.44 gh	75.52 f	67.37 f	66.67 de	36.20 b	36.32 ab	7.497 cd	7.200 d
$^2/_3$ NPK + $SiNPs_{50}$	76.33 f	76.37 e	68.02 f	67.63 d	36.58 a	35.83 b	7.735 c	7.810 b
$^2/_3$ NPK + $SiNPs_{100}$	77.36 e	77.36 d	70.18 cd	69.92 bc	34.92 de	33.89 d	7.497 cd	7.735 bc
$^2/_3$ NPK + $SiNPs_{200}$	77.95 d	77.93 c	70.58 b-d	70.61 a-c	34.68 de	34.07 d	8.214 bc	7.110 d
N_0:P_0:K_0 (0 NPK)	74.97 h	74.90 g	65.60 h	66.04 e	36.50 ab	36.53 a	6.670 d	6.840 f
F. test	**	**	**	**	**	**	**	**

Columns with different lowercase letters indicate a significant difference at $p \leq 0.05$. **, a significant effect at $p \leq 0.01$. The means of each factor designated at $p \leq 0.05$ level using Duncan's Multiple Range Test. NPK = Mineral NPK; PNPs = Phosphorus nanoparticles; ZnNPs = Zinc nanoparticles; SiNPs = Silicon nanoparticles.

4. Discussion

At harvest, the increase in the entire number of panicles m^{-2}, filled grains panicle^{-1}, and panicle length may occur due to the role of amino acids for increasing growth-promoting substances within plant tissues [40]. The improvement in panicle length might be due to the vital role of Zn in maintaining the structural stability of cell membranes and its use in protein synthesis, membrane function, and cell elongation [41]. Zinc is an essential micronutrient required for optimal plant growth [42]. In comparison to no nutrient input, the higher concentration of zinc applied as a foliar treatment allowed for a 26% increase in the number of panicles m^2. [43]. Additionally, the positive effects on the number of panicles m^{-2} at harvest, the weight of the filled grains per panicle, and the length of the panicle may be attributable to the use of rock phosphate in a nano form, which may increase the availability of phosphorus to plants by preventing soil fixation and removing the need for silicic acid, iron, and calcium, which are required for phosphorus fixation [44]. Moreover, rice leaf epidermal cell wall thickness is increased by SiNPs [45]. Nano silicon foliar application shows positive effects on growth and yield, especially when higher concentrations are used [46]. The increase in the number of grains panicle^{-1} and percentage of filled grains by foliar application with ZnNPs with the basal application of mineral NPK may be due to the possible roles of zinc in protecting plant cells from damage by reactive oxygen species and its effect on plant metabolism [47,48]. Zinc is an important element in various metabolic and physiological processes in the plant, where it activates some enzymes, and regulates the metabolism of carbohydrates and proteins, which are substantial for different processes in plant cells [49]. The benefits of nanomaterial-based formulations include the improvement in efficacy due to the higher surface area, higher solubility, induction of systemic activity due to smaller particle size and higher mobility, and lower toxicity due to the elimination of organic solvents when compared to conventionally used pesticides and their formulations. The positive effects of SiNPs on the number of grains panicle^{-1} and the percentage of filled grains may be due to these benefits [50]. The application of 2 mM of Si L^{-1} during the reproductive stages of rice can increase the number of filled grains per panicle [51,52]. The unfertilized treatment produced the highest grain weight, and the rise with the lowest dose of fertilizer is primarily due to a reduction in the number of spikelet's panicle^{-1}, which increases the filling spikelet's panicle^{-1} [53,54].

Because zinc promotes N absorption while also giving other necessary minerals to the plant and boosting the plant's metabolic process, nano zinc raised the N uptake [55]. Using Zn as a nanoparticle promoted rice development by releasing nutrients slowly and progressively during the critical growth stage. Nano silicon and nano phosphorus also elevate N uptake in the grain and straw. Silicon plays a major role in increasing rice protein content because it provides other nutrients to the plant, such as N and Si, and the Zn treatment by NPs had superior effects on the rice tissue [56]. Minor amounts of Si and Zn employed as nanoscale fertilizers provided benefits comparable to or greater than huge quantities of mineral fertilizers. Combining Si and Zn as NP could boost yield and element accumulation in rice grain, potentially lowering the frequency of dietary Si and Zn deficits in humans. As a result, more emphasis should be placed on Si and Zn nutrition in rice plants cultivated in soils deficient in these elements [57]. Silicon increased nitrogen and phosphate levels in rice grains and straw [58] and increased the N uptake by roots, shoots, and grains when compared to the NK + Si treatment These increased nitrogen uptakes may be attributed to lead erectness, which facilitated better penetration of sunlight, resulting in a higher photosynthetic activity of the plant and higher carbohydrate production. Silicate foliar treatments had a significant impact on nitrogen concentration and uptake value [59–61]. Nano Zn and Si increased P uptake, and silicon application increased phosphate uptake in rice, which directly correlates with increased growth and yield [58]. Si can improve and expand P availability. Other metals, such as Mn and Fe, control the internal accessibility of P in p-deficiency [62]. As a result, Si can indirectly increase P accessibility by decreasing the availability of Fe and Mn in plants [63], and silicon deposited on the roots and/or a Si-induced decrease in transpiration may be responsible for the decreased P uptake when the P concentration in the medium is high. Si has been discovered in the endodermal cells of many plant species' roots. P-uptake rates are likely to increase when P is reapplied [64]. Silicon concentration was found to be positively correlated with K concentration in shoots. [56,65] discovered that silicon could increase K absorption, uptake, and transport. Si and Zn had substantial interaction effects on Zn content in the root and shoot, as well as plant growth; administration of nano-Si (2.5 mM) to rice roots and shoots enhanced Zn concentration [15]. Increased Zn application may result in higher Zn concentrations in various parts of the rice plant due to increased Zn absorption in rice plants from soil solution [66]. Because Zn uptake through the plant's root is limited, the foliar application appears to be the most advantageous method because there is no such issue with foliar application [67]. The concentration and absorption of Zn in the rice grain and straw were improved by the addition of Si. Adding Si by foliar feeding caused the Zn content of rice to rise by nearly 21% [68]. All Zn application techniques (soil application, foliar application, seed priming, and seed coating) enhanced the Zn concentration in rice grains and Zn administration via foliar spray (0.5 percent Zn solution) or soil application (10 kg Zn ha^{-1}) enhanced the grain yield by nearly 30% in comparison to the control treatment [69]. When compared to no Si application, rice grain production decreased by 89, 51, 33, and 32 percent under treatments of 1, 10, 50, and 100 g L^{-1} Zn, respectively; however, the application of Si significantly increased the grain Zn content by 85% [70]. In contrast, adding Zn to the rice harvest increased the Si concentration by 24% [68].

ZnNPs increased the grain and straw yield and Zn has a significant positive effect on numerous enzymes, protein synthesis, the metabolism of carbohydrates and phosphate, gene expression and regulation, and safety of the ribosome structure [71]. Plants can absorb ZnO nanoparticles and can synthesize ZnONPs from foliar applications [72]. Using nanoscale zinc oxide had a significant effect on germination, growth, and yield [73]. SiNPs improved the yield; this may be due to the fact that a high concentration of SiNPs can reduce the severity of disease, with associated yield increases over infected plants that were not fertilized with Si [74]. Si is an essential nutrient and its absence causes imbalances of other nutrients resulting in poor growth if not the death of the plant [75]. Foliar fertilization can improve the efficiency and rapidity of the utilization of a nutrient urgently required by the plant for maximum growth and yield [76,77]. Nano fertilizer application promoted the growth, development, and antioxidant activity in rice and has the potential to improve crop production and plant nutrition [78–80]. The application of nanoparticles to plants can be beneficial for growth and development due to their ability for greater absorbance and high reactivity [13,81,82]. In general, when different nanoparticles could be applied on plant leaf surfaces in foliar feeding, they can enter through the stomata pores moving towards various plant tissues [83]. Rice's grain output increased by 45% when 2 mM of Si L^{-1} was administered during the reproductive growth stage of the plant [51]. By enhancing panicle fertility, the application of Si increases rice grain production [84]. When the plants are grown in the absence of Si, the dry matter accumulation in the grain was reduced [85].

The increase in hulling and milling percentages may be because the applied foliar application can enter the leaves either through many steps by penetrating the cuticle or entering through the plasmodesmata before entering the plant cell where they can be used in metabolism [76,86]. The positive effects on grain quality may be due to the nano fertilizer application promoting the growth, development, and antioxidant activity in rice, nutrient use efficiency, better yield, and reduced soil pollution [87,88]. SiO_2 NPs increase the photosynthetic rate by changing the activity of carbonic anhydrase and the synthesis of photosynthetic pigments [89]. Broken rice% is significantly reduced with nano fertilizers, which can improve the nutrition of the plant, enhance the efficient use of nutrition, and protect cultivated plants from different environmental stresses [90]. Increased protein content in the grain is due to an increase in the nitrogen content and increases the dry weight of the grain [91–93]. Because silicon provides additional nutrients such as nitrogen to the plant, it has a significant impact on boosting rice's protein content [45]. The Zn application raises the N metabolism, which increases amino acid production and protein synthesis, improving rice's protein content [94,95].

5. Conclusions

The study's findings indicated that the best methods for enhancing rice production were basal applications of $N_{165}P_{36}K_{60}$ or the recommended doses of mineral NPK fertilization alone, along with foliar applications of Zn_{50}NPs or two-thirds of the recommended dose of NPK fertilization. Applied nano fertilizers during the rice booting stage, two-thirds of the recommended doses of mineral NPK fertilization as a basal application + foliar application of P_{300}0NPs or two-thirds of the required dose of mineral NPK fertilization as a basal application + foliar application of Si_{200}NPs, can also increase yield and its characteristics. By combining the basal application of NPK fertilizers with the foliar application of nano fertilizers, it is possible to reduce the consumption of mineral NPK fertilizers by one-third and minimize soil contamination. Future research should compare the foliar and basal application of nanoparticles with multiple concentrations, forms, and application methods on Egyptian rice varieties, built around the findings of this study.

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