



Research article

Effects of using titanium dioxide nanoparticles in seed submersion and soil amendment on rice growth and yield

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Article Info

Article history:

Received 19 June 2024

Revised 3 September 2024

Accepted 5 September 2024

Available online 30 September 2024

Keywords:

Khao Dok Mali 105 rice,
Pathum Thani 1 rice,
Seed submersion,
Soil amendment,
Titanium dioxide nanoparticles

Abstract

Importance of the work: Titanium dioxide nanoparticles (TNPs) can enhance rice production; however, few studies have systematically investigated the effects of both TNP size and concentration.

Objectives: To determine the effects of TNPs in seed submersion and soil amendments on rice growth and yield.

Materials and Methods: A two-factor completely randomized design was used. Suspensions of 23 nm, 104 nm and 486 nm diameter TNPs were prepared at concentrations of 0–1,000 mg/L. Pathum Thani 1 and Khao Dok Mali 105 (KDML105) rice seeds were submerged. The soil was amended with TNPs. Rice growth, rice yield and titanium accumulation were recorded.

Results: TNP treatments promoted plant height, chlorophyll content, the number of tillers per plant, weight and the number of good-quality seeds. TNPs had no effect on yield quality. Larger TNPs at a higher concentration led to greater plant height and chlorophyll content in both cultivars. Smaller TNPs at higher concentrations led to greater titanium accumulation in rice. The improvement of rice growth by TNPs was due to the promotion of photosynthesis. Smaller TNPs could penetrate rice tissues more readily, causing greater bioaccumulation. Larger TNPs agglomerated less in water, entered cytoplasm more efficiently and thus promoted photosynthesis more effectively. However, improved photosynthesis alone would not be sufficient for enhancing yield and yield quality.

Main finding: The combination of seed submersion and soil amendment with 486 nm TNPs at 1,000 mg/L concentration was recommended for improving rice growth. Future studies should explore the use of TNPs with other fertilizers to enhance rice yield and yield quality.

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<https://doi.org/10.34044/j.anres.2024.58.5.04>

Introduction

Nanotechnology is a key path toward sustainable agriculture that can address the impacts of climate change on crop production (Usman et al., 2020). Due to their small sizes and unique properties, nanoparticles can enhance plant production more efficiently than traditional materials (Singh et al., 2021). Nano-fertilizers used in small quantities provide sufficient nutrients to plants, while reducing soil contamination, due to their high absorption rate into plants (Butt and Naseer, 2020) and high biochemical specificity (Verma et al., 2022). Encapsulated nano-pesticides ensure the delivery of active ingredients to specific targets and thus are less harmful to other beings than conventional choices (Wang et al., 2022). Nanomaterials are also implemented as soil and plant biosensors (Johnson et al., 2021) and soil remediation agents (Hussain et al., 2022). Nanoparticles have been demonstrated to improve the growth, yield and yield quality of various crops (Wang et al., 2020; Jakhar et al., 2022). The production of rice, one of the most important sources of food, can also be enhanced by the use of nanoparticles (Wang et al., 2021). However, excessive use and inappropriate choices of particle size can have negative effects on plant growth (El-Moneim et al., 2021). Thus, the usage of nanomaterials in rice production must be carefully considered.

Various types have been explored in agriculture, including organic (Chandel et al., 2022), metallic (Kale et al., 2021) and metal oxide (Dola et al., 2022; Zhou et al., 2023) nanoparticles. Titanium dioxide (TiO₂) nanoparticles (TNPs) have received considerable interest in agricultural research (Rodríguez-González et al., 2019) due to their photocatalytic capabilities when exposed to ultraviolet light (Mohadesi et al., 2022). Activated TNPs efficiently generate excited electrons, which can react with oxygen and water to create reactive oxygen species (ROS) (Ma et al., 2019). In rice, generated ROS can induce the activities of antioxidants such as superoxide dismutase and peroxidase (Rizwan et al., 2019). Due to the similarity in the chemical properties of titanium and iron ions, TNPs can improve the electron transport chain facilitated by iron-containing complexes in photosystem I and thus promote photosynthesis (Cigler et al., 2010). TNPs have been widely used in several industries, including cosmetics and food (Hsu et al., 2024). Thus, the mass production of TNPs can substantially improve cost-effectiveness in agriculture (Parrino and Palmisano, 2020). Indeed, long-term use of

TNPs provides more nutrients to plants and reduces the net cost of fertilizers (Kumar et al., 2023). However, some studies revealed negative effects of TNPs on rice growth and yield (Faraz et al., 2020). Currently, no clear consensus has been established regarding the effects of TNPs on rice.

The effects of the variation in TNP sizes have been scarcely explored in studies on the impacts of TNPs on plants. Debnath et al. (2020) investigated the submersion of rice seeds in TNP suspensions of varying concentrations but only using one size (<100 nm) of TNPs. They reported that TNP concentrations of 20 parts per million (ppm) and 50 ppm were the most beneficial to rice seedling growth and grain yield. In contrast, Ji et al. (2017) showed that the submersion of rice seeds in 21 nm diameter TNP suspensions with concentrations of 10 ppm, 100 ppm and 1,000 ppm reduced root length and plant height. Additionally, TNPs can be added to the soil. For example, Zahra et al. (2017) investigated the addition of 20 nm diameter TNPs in P-deficient soil and the rice response. They reported that the addition of TNPs at 50–750 ppm increased shoot length and dry weight. However, Waani et al. (2021) revealed that the addition of 26.5 nm diameter TNPs into a silt-loam soil at 500–700 ppm reduced root length, shoot length and rice biomass. The effects of TNP size cannot be determined from these studies due to the differences in experimental conditions and the lack of size variation. A systematic study that varied both size and concentration would elucidate the proper usage of TNPs in rice production.

Theerak et al. (2023) and Theerak (2024) studied the effects of TNP size and concentration on rice growth and yield when rice seeds were submerged in TNP suspensions. In the early development of rice, the treatments with larger TNPs improved seedling and plant height, fresh and dry weight, as well as the survival rate more than those with smaller TNPs (Theerak et al., 2023). However, Theerak (2024) revealed that on days 90 and 120, the TNP exposure improved only rice plant height but had no impact on rice yield. While these studies revealed the limitations of TNPs, their usage was only implemented via seed submersion. Amending soil with TNPs is another viable method that could be used in conjunction with seed submersion. Therefore, the current work investigated for the first time the effects of TNP size and concentration on the combined usage of TNPs. The results of this study should provide a more comprehensive understanding of TNP usage for rice cultivation.

Materials and Methods

An experiment with a complete randomized design with two factors (size and concentration) was conducted to investigate the use of TNPs (anatase) in the form of colloidal suspensions in rice seed submersion and soil amendment. The three nominal TNP sizes were 20–30 nm (small), 80–120 nm (medium) and 400–600 nm (large) in diameter. The six TNP concentrations were 0 mg/L, 10 mg/L, 50 mg/L, 100 mg/L, 250 mg/L and 1,000 mg/L. Two rice cultivars were studied—Pathum Thani 1 and Khao Dok Mali 105 (KDML105)—being photoperiod insensitive and sensitive, respectively. Pathum Thani 1 rice was selected because of its high yield and popularity among local farmers. KDML105 rice was chosen due to the high demand from consumers and its aromatic scent. Each treatment was repeated three times, with each repetition consisting of three pots.

TNPs were collected based on Theerak et al. (2023) and Theerak (2024) and used without modification. Briefly, the small and medium TNPs were purchased from US Research Nanomaterials Inc., while the large TNPs were synthesized via a modified sol-gel method (Tian et al., 2015). TNP size was characterized via scanning and transmission electron microscopy. The dynamic light scattering technique was used to investigate the agglomeration behavior of the TNPs and to measure the average hydrodynamic size. An IKA T25 digital Ultra-Turrax sonicator probe was used to prepare TNP suspensions of various concentrations at a speed of 1,000 rpm for 30 min to improve TNP dispersion. Before the experiment, the rice seeds were washed with clean water; only good-quality seeds were selected for the experiment. The soil used for this work was acquired from a local farm in Tumbon Khlong Ha, Khlong Laung district, Pathum Thani province, Thailand. The soil sample was characterized via proximate analysis at the Science Center, Valaya Alongkorn Rajabhat University under Royal Patronage, to quantify its pH, electrical conductivity, organic content, nitrogen content, phosphate content, potassium content and carbon-to-nitrogen ratio. The results of the soil analysis are presented in Table 1. To determine the Ti content in the soil, soil samples were dissolved in a 1:3 mixture of concentrated hydrochloric acid and concentrated nitric acid and then digested in closed vessels at 180°C for at least 30 min, until the solutions became clear. The solutions were diluted until the acid concentration reached 1% and were then characterized using inductively

coupled plasma mass spectrometry (ICP-MS; Shimadzu ICPMS-2030).

In each treatment, 15 healthy rice seeds were submerged in 10 mL of a TNP suspension for 48 hr. The rice growth experiment began on 3 August 2022, for both cultivars, so that they were both ready for harvest on 1 December 2022. Thus, the total growth period was 120 d. The rice seeds were transferred to a plastic pot (20 cm in diameter) filled with the local soil. The rice plants were watered daily and no other fertilizers were added. On average, the temperature was 32–35°C in the morning and 36–39 °C in the afternoon. After 25 d, 20 mL of the various TNP suspensions of similar size and concentration was added to separate pots of soil. The number of days until 50% flowering and until 50% harvest were recorded. On day 120, measurements were recorded of: plant height, leaf color (SPAD index), number of tillers per hill, fresh and dry weights, number of seeds per panicle, percentage of good-quality seeds and seed weight, width and length. Soil properties and seed nutrient profiles (starch, protein, fat, ash, humidity, calcium and potassium contents) were determined via proximate analysis. The Ti contents in each of the soil, rice roots, rice stems, rice leaves and rice grains were quantified using ICP-MS. The samples of rice roots, stems, leaves, and seeds were thoroughly washed with deionized water and ground separately. Then samples were prepared using the same procedure in preparation for ICP-MS. The collected data were analyzed based on a one-way analysis of variance using Fisher's least significant difference and a two-way analysis of variance using Tukey's honestly significant difference test. Pearson correlation coefficients were computed between significant variables.

Table 1 Properties of soil used for this work

Soil property	Value
pH	6.5
Electrical conductivity (mS/cm)	4.5
Organic matter (%)	1.30
Total N (%)	1.06
Total P ₂ O ₅ (%)	1.31
Total K ₂ O (%)	2.52
Carbon-to-nitrogen ratio	1.6

Results and Discussion

The average sizes of the small, medium and large TNPs were 23 nm, 104 nm and 486 nm, respectively, while the average hydrodynamic sizes of the small, medium and large TNPs were 6.2 μm , 3.5 μm and 0.45 μm , respectively. The impact of TNP exposure on the plant height of the Pathum Thani 1 and KDML105 rice samples and the corresponding one-way analysis of variance results are shown in Table 2. TNP treatment highly significantly ($p < 0.01$) increased plant height for both rice cultivars, with the treatments with a higher concentration and larger TNP size showing better improvement. The two-way analysis of variance analysis (not shown in the Table) confirmed that the effects of TNP size and concentration and their interaction effects were highly significant ($p < 0.01$). The effects of TNP exposure on the SPAD indices of rice leaves, indicating chlorophyll content, were similar, as shown in Table 2. This similarity in the effects was confirmed by the positive correlation coefficients between plant height and SPAD index for both the Pathum Thani 1 and KDML105 rice cultivars, as shown in Figs. S1 and S2, respectively. However, there were some differences in plant response based on the effects of the TNPs on other growth quantities. As shown in Table 3, the TNP treatments enhanced the number of tillers per hill for both rice cultivars; however, according to the two-way analysis of variance, only the TNP concentration had a significant effect. Furthermore, among the treatments

with TNP concentrations above the control level, the effects were not different, indicating that increasing the TNP concentration above 10 mg/L provided no additional benefits and was thus wasteful. The effects of TNPs on the number of days until 50% flowering and 50% harvest (shown in Table 4) were similar to the effects on the number of tillers per hill. Nevertheless, despite the differences, these growth parameters were all positively correlated, according to Figs. S1 and S2.

Table 3 Number of tillers per hill of two rice varieties (Pathum Thani 1: PT 1 and Khao Dok Mali 105: KDML 105) subjected to titanium dioxide nanoparticle (TNP) exposure

TNP concentration (mg/L)	Number of tillers per hill for TNP size (nm)		
	20–30	80–120	400–600
PT 1			
0	4.50 $\pm$ 0.84 ^b	4.50 $\pm$ 0.84 ^b	4.50 $\pm$ 0.84 ^b
10	12.83 $\pm$ 0.98 ^a	13.17 $\pm$ 1.33 ^a	14.17 $\pm$ 1.17 ^a
50	14.00 $\pm$ 1.10 ^a	14.00 $\pm$ 0.63 ^a	12.83 $\pm$ 0.98 ^a
100	13.33 $\pm$ 0.82 ^a	14.17 $\pm$ 1.17 ^a	13.67 $\pm$ 1.21 ^a
250	12.83 $\pm$ 0.75 ^a	13.83 $\pm$ 1.17 ^a	13.50 $\pm$ 1.38 ^a
1,000	14.00 $\pm$ 1.26 ^a	13.17 $\pm$ 1.17 ^a	14.17 $\pm$ 0.75 ^a
<i>p</i> -value, %CV	<0.001, 29.5	<0.001, 29.9	<0.001, 29.9
(KDML105) 0			
0	3.67 $\pm$ 0.52 ^b	3.67 $\pm$ 0.52 ^b	3.67 $\pm$ 0.52 ^b
10	9.67 $\pm$ 1.21 ^a	9.83 $\pm$ 1.33 ^a	9.83 $\pm$ 1.17 ^a
50	10.17 $\pm$ 0.75 ^a	9.33 $\pm$ 1.37 ^a	9.83 $\pm$ 1.33 ^a
100	10.17 $\pm$ 1.33 ^a	10.17 $\pm$ 1.17 ^a	9.67 $\pm$ 1.21 ^a
250	9.67 $\pm$ 1.21 ^a	9.83 $\pm$ 1.47 ^a	9.33 $\pm$ 1.37 ^a
1,000	9.67 $\pm$ 1.21 ^a	8.83 $\pm$ 0.76 ^a	9.33 $\pm$ 1.03 ^a
<i>p</i> -value, %CV	<0.001, 29.0	<0.001, 29.3	<0.001, 29.0

CV = coefficient of variance; Values (mean $\pm$ SD) in same column with different lowercase superscripts are highly significantly ($p < 0.01$) different.

Table 2 Plant height and leaf SPAD index of two rice varieties (Pathum Thani 1: PT 1 and Khao Dok Mali 105: KDML 105) subjected to titanium dioxide nanoparticle (TNP) exposure

TNP concentration (mg/L)	Plant height (cm) for TNP size (nm)			SPAD index for TNP size (nm)		
	20–30	80–120	400–600	20–30	80–120	400–600
PT 1						
0	72.22 $\pm$ 0.34 ^f	72.22 $\pm$ 0.24 ^e	72.22 $\pm$ 0.25 ^f	11.06 $\pm$ 0.07 ^f	11.06 $\pm$ 0.07 ^e	11.06 $\pm$ 0.07 ^e
10	104.27 $\pm$ 0.37 ^e	109.71 $\pm$ 0.37 ^d	110.64 $\pm$ 0.59 ^e	11.81 $\pm$ 0.03 ^e	11.68 $\pm$ 0.56 ^{de}	13.67 $\pm$ 1.11 ^d
50	106.63 $\pm$ 0.54 ^d	110.30 $\pm$ 0.25 ^d	112.78 $\pm$ 0.21 ^d	12.48 $\pm$ 0.13 ^d	12.71 $\pm$ 0.47 ^{cd}	14.56 $\pm$ 1.18 ^{cd}
100	107.38 $\pm$ 0.23 ^c	112.56 $\pm$ 0.28 ^c	115.45 $\pm$ 0.28 ^c	13.45 $\pm$ 0.11 ^c	13.51 $\pm$ 0.50 ^c	15.07 $\pm$ 0.63 ^{bc}
250	108.70 $\pm$ 0.30 ^b	113.25 $\pm$ 0.26 ^b	116.26 $\pm$ 0.26 ^b	14.62 $\pm$ 0.07 ^b	14.78 $\pm$ 0.48 ^b	16.48 $\pm$ 0.57 ^{ab}
1,000	109.82 $\pm$ 0.40 ^a	116.26 $\pm$ 0.55 ^a	117.23 $\pm$ 0.55 ^a	16.12 $\pm$ 0.11 ^a	16.16 $\pm$ 0.67 ^a	18.23 $\pm$ 0.25 ^a
<i>p</i> -value, %CV	<0.001, 13.2	<0.001, 14.5	<0.001, 15.0	<0.001, 13.3	<0.001, 13.9	<0.001, 16.1
KDML105						
0	75.06 $\pm$ 1.20 ^d	75.06 $\pm$ 1.20 ^d	75.06 $\pm$ 1.20 ^d	13.33 $\pm$ 0.39 ^e	13.33 $\pm$ 0.39 ^d	13.33 $\pm$ 0.39 ^c
10	107.36 $\pm$ 1.08 ^c	112.59 $\pm$ 1.38 ^c	113.56 $\pm$ 1.69 ^c	14.56 $\pm$ 0.50 ^{de}	14.62 $\pm$ 1.37 ^{cd}	16.94 $\pm$ 1.64 ^b
50	109.62 $\pm$ 1.19 ^b	113.59 $\pm$ 0.86 ^{bc}	115.40 $\pm$ 1.59 ^c	15.17 $\pm$ 0.65 ^{cd}	15.75 $\pm$ 1.03 ^{bd}	17.77 $\pm$ 1.11 ^b
100	109.65 $\pm$ 1.11 ^b	115.52 $\pm$ 2.11 ^b	118.76 $\pm$ 1.76 ^b	16.77 $\pm$ 1.01 ^c	16.73 $\pm$ 0.97 ^{bc}	17.69 $\pm$ 1.08 ^b
250	110.80 $\pm$ 1.05 ^b	115.56 $\pm$ 0.72 ^b	119.42 $\pm$ 0.91 ^b	17.48 $\pm$ 0.66 ^b	17.77 $\pm$ 0.81 ^b	19.35 $\pm$ 0.64 ^b
1,000	112.93 $\pm$ 1.11 ^a	120.00 $\pm$ 1.46 ^a	121.93 $\pm$ 0.52 ^a	20.26 $\pm$ 0.42 ^a	20.58 $\pm$ 0.49 ^a	22.59 $\pm$ 0.26 ^a
<i>p</i> -value, %CV	<0.001, 12.8	<0.001, 14.3	<0.001, 14.9	<0.001, 14.6	<0.001, 15.3	<0.001, 16.5

CV = coefficient of variance; Values (mean $\pm$ SD) in same column with different lowercase superscripts are highly significantly ($p < 0.01$) different.

Table 4 Days until 50% flowering and 50% harvest of two rice varieties (Pathum Thani 1: PT 1 and Khao Dok Mali 105: KDML 105) subjected to titanium dioxide nanoparticle (TNP) exposure

TNP concentration (mg/L)	%50 flowering (days) for TNP size (nm)			%50 harvest (days) for TNP size (nm)		
	20–30	80–120	400–600	20–30	80–120	400–600
PT 1						
0	94.33±1.03 ^b	94.33±1.03 ^b	94.33±1.03 ^b	111.83±0.75 ^b	111.83±0.75 ^b	111.83±0.75 ^b
10	101.33±1.75 ^a	102.00±1.26 ^a	102.00±1.41 ^a	123.83±0.75 ^a	124.67±1.21 ^a	125.50±1.38 ^a
50	102.33±1.37 ^a	102.17±1.60 ^a	101.33±0.82 ^a	124.67±1.21 ^a	125.00±0.63 ^a	126.00±0.89 ^a
100	103.00±1.10 ^a	102.67±1.51 ^a	102.00±1.41 ^a	125.50±1.38 ^a	125.67±1.21 ^a	125.67±1.21 ^a
250	101.33±1.21 ^a	103.83±0.41 ^a	101.83±1.47 ^a	126.00±1.26 ^a	125.17±1.60 ^a	125.50±1.38 ^a
1,000	102.17±1.17 ^a	101.50±1.76 ^a	101.83±1.47 ^a	125.17±0.75 ^a	124.83±1.47 ^a	125.33±1.03 ^a
<i>p</i> -values, %CV	<0.001, 3.2	<0.001, 3.4	<0.001, 3.1	<0.001, 4.2	<0.001, 4.1	<0.001, 4.2
KDML105						
0	105.17±0.75 ^b	105.17±0.75 ^b	105.17±0.75 ^b	119.67±1.03 ^b	119.67±1.03 ^b	119.67±1.03 ^b
10	111.50±1.05 ^a	111.67±1.03 ^a	112.83±1.83 ^a	134.50±1.38 ^a	134.50±1.76 ^a	135.67±1.51 ^a
50	112.83±1.60 ^a	112.83±1.17 ^a	112.67±1.51 ^a	135.83±1.60 ^a	134.17±1.47 ^a	136.00±0.89 ^a
100	113.17±0.98 ^a	111.50±1.38 ^a	112.17±1.33 ^a	135.67±0.82 ^a	134.67±1.03 ^a	135.17±1.17 ^a
250	112.00±0.63 ^a	112.33±1.51 ^a	112.33±1.51 ^a	135.17±1.47 ^a	136.00±1.55 ^a	135.83±0.75 ^a
1,000	111.33±1.03 ^a	111.50±1.52 ^a	111.17±1.60 ^a	135.83±1.83 ^a	135.00±1.55 ^a	135.83±1.17 ^a
<i>p</i> -value, %CV	<0.001, 2.6	<0.001, 2.6	<0.001, 2.7	<0.001, 4.6	<0.001, 4.5	<0.001, 4.6

CV = coefficient of variance; Values (mean ± SD) in same column with different lowercase superscripts are highly significantly ($p < 0.01$) different.

In addition, the effects were not uniform of TNPs on rice yield and yield quality. Table 5 summarizes the positive effects of TNPs on the fresh and dry weights of both rice cultivars. The two-way analysis of variance showed that the effects of size and concentration and the interaction between both effects were highly significant ($p < 0.01$). However, there was no difference among the treatments with TNP concentrations above 10 mg/L for each TNP size, which was similar to the TNP effects on the number of tillers per hill. In Table 6, the number of seeds and the percentage of good-quality seeds were positively influenced by the TNP treatments. Similar to the effects on fresh and dry weight, increasing the TNP concentrations beyond 10 mg/L did not have a positive

impact on those seed qualities, though both the size and concentration effects were significant, as was their interaction. Still, these positive effects were positively correlated (Figs. S1 and S2) with the effects of TNP on rice growth and chlorophyll content, showing the link between the promotion of photosynthesis by TNPs and rice yield. However, as shown in Table 7 and Tables S1–S5, the TNP treatments had no significant ($p > 0.05$) effects on seed weight, seed width, seed length and the seed nutrient profile, which consisted of the contents of starch, protein, fat, humidity, ash, calcium and potassium. Therefore, while the application of TNPs alone improved the growth and some yield parameters of both rice cultivars, it did not enhance the yield quality.

Table 5 Fresh and dry weight of two rice varieties (Pathum Thani 1: PT 1 and Khao Dok Mali 105: KDML 105) subjected to titanium dioxide nanoparticle (TNP) exposure

TNP concentration (mg/L)	Fresh weight (g) for TNP size (nm)			Dry weight (g) for TNP size (nm)		
	20–30	80–120	400–600	20–30	80–120	400–600
PT 1						
0	45.52±1.43 ^b	45.52±1.43 ^b	45.52±1.43 ^b	6.50±0.88 ^b	6.50±0.88 ^b	6.50±0.88 ^b
10	201.34±1.69 ^a	268.13±1.55 ^a	351.20±2.42 ^a	24.50±0.81 ^a	36.80±3.23 ^a	39.90±3.54 ^a
50	199.78±1.02 ^a	272.49±1.55 ^a	349.41±3.92 ^a	24.46±2.76 ^a	33.65±4.07 ^a	48.95±3.67 ^a
100	201.20±1.51 ^a	270.90±3.01 ^a	349.93±3.20 ^a	23.63±2.52 ^a	36.00±5.00 ^a	44.29±7.06 ^a
250	201.30±1.35 ^a	269.29±2.60 ^a	351.60±3.48 ^a	24.78±2.50 ^a	38.72±4.44 ^a	43.87±7.65 ^a
1,000	201.21±1.70 ^a	271.77±3.38 ^a	349.47±3.26 ^a	24.94±2.96 ^a	33.03±4.34 ^a	44.23±7.42 ^a
<i>p</i> -value, %CV	<0.001, 33.6	<0.001, 36.5	<0.001, 38.5	<0.001, 33.1	<0.001, 38.2	<0.001, 40.6
KDML105						
0	36.44±1.32 ^b	36.44±1.32 ^b	36.44±1.32 ^b	4.94±0.66 ^b	4.94±0.66 ^b	4.94±0.66 ^b
10	151.86±1.57 ^a	171.24±1.89 ^a	201.99±2.23 ^a	21.31±2.51 ^a	25.12±3.27 ^a	28.83±4.10 ^a
50	152.68±1.54 ^a	170.91±2.56 ^a	199.60±3.22 ^a	21.50±1.97 ^a	25.62±3.03 ^a	31.29±2.53 ^a
100	149.19±1.82 ^a	172.08±1.84 ^a	200.94±2.44 ^a	21.02±3.26 ^a	24.48±3.10 ^a	26.23±2.68 ^a
250	151.42±1.20 ^a	171.72±2.35 ^a	202.07±2.52 ^a	21.06±0.86 ^a	24.18±3.73 ^a	27.90±2.76 ^a
1,000	150.08±1.66 ^a	169.39±1.99 ^a	200.79±2.46 ^a	21.72±1.73 ^a	27.54±2.75 ^a	27.74±3.78 ^a
<i>p</i> -value, %CV	<0.001, 32.8	<0.001, 34.2	<0.001, 35.9	<0.001, 34.9	<0.001, 37.6	<0.001, 38.4

CV = coefficient of variance; Values (mean ± SD) in same column with different lowercase superscripts are highly significantly ($p < 0.01$) different.

Table 6 Number of seeds and percent of good-quality seeds of two rice varieties (Pathum Thani 1: PT 1 and Khao Dok Mali 105: KDML 105) subjected to different titanium dioxide nanoparticle (TNP) sizes

TNP concentration (mg/L)	Number of seeds for TNP size (nm)			Percent of good-quality seeds (%) for TNP size (nm)		
	20–30	80–120	400–600	20–30	80–120	400–600
PT 1						
0	29.50±0.84 ^b	29.50±0.84 ^b	29.50±0.84 ^b	2.34±0.39 ^c	2.34±0.39 ^c	2.34±0.39 ^c
10	149.33±3.98 ^a	164.50±2.43 ^a	178.67±3.27 ^a	95.19±0.17 ^b	96.33±0.15 ^b	96.24±0.18 ^b
50	148.17±3.13 ^a	163.50±3.89 ^a	180.67±3.01 ^a	95.23±0.19 ^b	96.28±0.16 ^b	96.31±0.18 ^b
100	146.83±2.56 ^a	164.67±2.34 ^a	178.17±2.56 ^a	95.28±0.16 ^b	96.20±0.12 ^b	96.16±0.11 ^b
250	148.83±3.25 ^a	165.83±2.99 ^a	178.67±3.08 ^a	95.21±0.08 ^b	96.21±0.14 ^b	96.34±0.12 ^b
1,000	152.17±3.66 ^a	166.17±1.33 ^a	181.83±1.33 ^a	97.30±0.15 ^a	97.99±0.17 ^a	98.72±0.11 ^a
<i>p</i> -value, %CV	<0.001, 35.1	<0.001, 36.0	<0.001, 36.7	<0.001, 44.0	<0.001, 44.1	<0.001, 44.1
KDML105						
0	27.67±2.25 ^b	27.67±2.25 ^b	27.67±2.25 ^b	2.44±0.33 ^c	2.44±0.33 ^c	2.44±0.33 ^c
10	139.50±3.62 ^a	150.83±3.66 ^a	161.67±2.42 ^a	95.23±0.14 ^b	96.32±0.19 ^b	9.62±0.17 ^b
50	138.83±2.71 ^a	152.50±1.87 ^a	158.83±3.49 ^a	95.24±0.18 ^b	96.24±0.16 ^b	96.35±0.20 ^b
100	137.83±3.19 ^a	150.83±2.79 ^a	161.33±1.86 ^a	95.20±0.09 ^b	96.20±0.13 ^b	96.24±0.19 ^b
250	140.00±2.10 ^a	150.50±3.33 ^a	160.67±4.18 ^a	95.34±0.15 ^b	96.27±0.16 ^b	96.18±0.16 ^b
1,000	141.17±1.17 ^a	152.33±1.03 ^a	162.00±1.63 ^a	97.22±0.16 ^a	97.95±0.13 ^a	98.65±0.17 ^a
<i>p</i> -value, %CV	<0.001, 35.0	<0.001, 35.8	<0.001, 36.4	<0.001, 44.0	<0.001, 44.0	<0.001, 44.1

CV = coefficient of variance; Values (mean ± SD) in same column with different lowercase superscripts are highly significantly ($p < 0.01$) different.

Table 7 Starch and protein content in grains from two rice varieties (Pathum Thani 1: PT 1 and Khao Dok Mali 105: KDML 105) subjected to titanium dioxide nanoparticle (TNP) exposure

TNP concentration (mg/L)	Starch content (%) in grains for TNP size (nm)			Protein content (%) in grains for TNP size (nm)		
	20–30	80–120	400–600	20–30	80–120	400–600
PT 1						
0	-	-	-	-	-	-
10	76.76±1.61	76.73±1.67	77.50±0.90	6.79±0.76	7.28±0.41	6.63±0.40
50	76.80±1.29	77.08±1.57	76.94±1.56	6.89±0.42	6.87±0.48	7.35±0.44
100	77.49±0.90	77.18±2.01	76.95±1.13	6.48±0.41	6.80±0.52	7.00±0.49
250	76.11±1.44	75.75±1.14	77.14±1.12	6.97±0.79	6.92±0.51	7.06±0.74
1,000	77.52±1.07	76.07±1.45	76.54±1.65	6.90±0.58	6.66±0.61	6.89±0.49
<i>p</i> -value, %CV	0.32, 1.70	0.46, 2.07	0.79, 1.62	0.66, 8.78	0.34, 7.52	0.23, 7.76
KDML105						
0	-	-	-	-	-	-
10	77.27±1.46	76.31±1.68	75.81±1.90	7.11±0.60	7.45±0.30	7.17±0.73
50	76.30±1.54	76.75±1.64	75.86±1.47	6.90±0.51	6.51±0.59	7.28±0.54
100	77.79±0.93	76.36±0.73	76.83±0.79	7.25±0.33	6.79±0.68	7.04±0.54
250	76.58±0.86	75.77±0.57	76.84±1.91	7.45±0.62	6.98±0.65	6.88±0.67
1,000	76.76±1.12	76.40±1.75	76.86±1.73	6.94±0.54	7.00±0.62	6.52±0.37
<i>p</i> -value, %CV	0.26, 1.62	0.81, 1.71	0.60, 2.06	0.38, 7.48	0.12, 9.01	0.22, 8.63

CV = coefficient of variance; - = no grains produced

Soil properties and Ti accumulation in soil were characterized to further investigate the effects of TNPs. Soil pH, electrical conductivity, organic matter, total nitrogen, total phosphate, total potash content and carbon-to-nitrogen ratio were not impacted by any TNP treatment compared to the control treatment. Compared to those properties before rice cultivation, soil electrical conductivity, organic matter, total nitrogen, total phosphate and total potash content decreased, while the carbon-to-nitrogen ratio increased. These changes represented nutrients in soil being consumed by rice plants and were expected since no fertilizers (other than the TNP) had been added during the treatment.

Ti accumulation in the soil in each treatment is shown in [Table 8](#). When higher concentrations of TNP and larger TNPs were applied, more Ti was found in the soil. The higher Ti in the soil under the treatments with larger TNPs applied at similar concentrations suggested that the size might have had an impact on the absorption of TNPs by the rice. Indeed, this effect could be observed in the ICP-MS data in [Tables 8 and 9](#), where Ti bioaccumulation in rice tissues was quantified. More Ti was accumulated in rice roots, stems and leaves when smaller TNP sizes and higher TNP concentrations were used. Therefore, smaller TNPs were more capable of passing through rice roots and reaching other plant parts.

Table 8 Titanium content in soil and roots of two rice varieties (Pathum Thani 1: PT 1 and Khao Dok Mali 105: KDML 105) subjected to titanium dioxide nanoparticle (TNP) exposure

TNP concentration (mg/L)	Ti in soil (ppb) for TNP size (nm)			Ti in roots (ppb) for TNP size (nm)		
	20–30	80–120	400–600	20–30	80–120	400–600
PT 1						
0	4.2±0.1 ^a	4.2±0.1 ^a	4.2±0.1 ^a	0.17±0.01 ^f	0.27±0.01 ^f	0.24±0.01 ^f
10	77±1.1 ^b	85±1.4 ^b	103±0.8 ^b	180.60±5.68 ^e	162.07±5.10 ^e	144.22±0.79 ^e
50	295±3.7 ^c	431±9.0 ^c	543±11 ^c	360.07±6.47 ^d	324.76±13.98 ^d	288.58±2.52 ^d
100	912±7.1 ^d	942±22 ^d	1,091±10 ^d	860.32±28.60 ^c	774.49±26.76 ^c	688.25±14.68 ^c
250	2,874±42 ^e	3,002±65 ^e	3,193±41 ^e	1280.81±44.25 ^b	1152.33±47.68 ^b	1024.50±43.24 ^b
1,000	10,119±22 ^f	10,375±9.0 ^f	11,412±12 ^f	2060.31±86.32 ^a	1854.27±63.89 ^a	1648.60±68.58 ^a
<i>p</i> -value, %CV	<0.001, 130	<0.001, 135	<0.001, 141	<0.001, 92.8	<0.001, 95.1	<0.001, 98.6
KDML105						
0	4.6±0.1 ^a	4.6±0.1 ^a	4.6±0.1 ^a	0.21±0.01 ^f	0.16±0.01 ^f	0.23±0.01 ^f
10	67±1.4 ^b	80±1.5 ^a	94±2.1 ^b	167.86±6.22 ^e	151.40±2.81 ^e	133.16±4.58 ^e
50	278±2.6 ^c	417±9.5 ^b	477±12 ^c	337.45±12.41 ^d	303.81±10.45 ^d	265.78±4.09 ^d
100	856±12 ^d	901±12 ^c	953±7.6 ^d	792.97±17.25 ^c	717.21±25.18 ^c	638.38±27.83 ^c
250	2,340±29 ^e	2,881±65 ^d	3,013±65 ^e	1194.85±21.36 ^b	1070.04±41.06 ^b	960.27±40.15 ^b
1,000	10,231±22 ^f	11,138±18 ^e	12,264±26 ^f	1903.23±41.07 ^a	1734.72±74.58 ^a	1517.46±70.93 ^a
<i>p</i> -value, %CV	<0.001, 138	<0.001, 132	<0.001, 129	<0.001, 92.5	<0.001, 98.9	<0.001, 94.6

ppb = parts per billion; CV = coefficient of variance; Values (mean ± SD) in same column with different lowercase superscripts are highly significantly ($p < 0.01$) different.

Table 9 Titanium content in stems and leaves of two rice varieties (Pathum Thani 1: PT 1 and Khao Dok Mali 105: KDML 105) subjected to titanium dioxide nanoparticle (TNP) exposure

TNP concentration (mg/L)	Ti in stems (ppb) for TNP size (nm)			Ti in leaves (ppb) for TNP size (nm)		
	20–30	80–120	400–600	20–30	80–120	400–600
PT 1						
0	0.25±0.01 ^f	0.29±0.01 ^f	0.23±0.01 ^f	0.13±0.01 ^f	0.25±0.01 ^f	0.10±0.01 ^f
10	2.14±0.01 ^e	1.48±0.06 ^e	2.01±0.08 ^e	2.82±0.03 ^e	2.33±0.06 ^e	2.51±0.11 ^e
50	3.36±0.07 ^d	3.15±0.10 ^d	2.64±0.08 ^d	5.31±0.21 ^d	5.10±0.20 ^d	4.35±0.15 ^d
100	7.39±0.18 ^c	6.56±0.13 ^c	5.82±0.18 ^c	11.86±0.05 ^c	11.27±0.41 ^c	10.04±0.22 ^c
250	9.89±0.21 ^b	8.61±0.24 ^b	7.97±0.21 ^b	17.75±0.51 ^b	16.05±0.14 ^b	13.99±0.53 ^b
1,000	15.50±0.36 ^a	14.62±0.58 ^a	13.16±0.45 ^a	28.22±0.60 ^a	25.49±0.79 ^a	22.53±0.39 ^a
<i>p</i> -value, %CV	<0.001, 83.1	<0.001, 86.7	<0.001, 89.5	<0.001, 90.3	<0.001, 89.0	<0.001, 88.4
KDML105						
0	0.24±0.01 ^f	0.23±0.01 ^f	0.12±0.01 ^f	0.19±0.01 ^f	0.23±0.01 ^f	0.16±0.01 ^f
10	1.72±0.04 ^e	1.94±0.01 ^e	1.49±0.03 ^e	2.45±0.08 ^e	2.84±0.08 ^e	2.08±0.04 ^e
50	3.36±0.08 ^d	2.37±0.03 ^d	2.30±0.04 ^d	4.59±0.12 ^d	4.72±0.11 ^d	4.12±0.07 ^d
100	6.46±0.24 ^c	6.23±0.27 ^c	5.62±0.16 ^c	10.93±0.52 ^c	10.26±0.21 ^c	9.29±0.38 ^c
250	9.36±0.23 ^b	8.29±0.10 ^b	7.52±0.06 ^b	16.35±0.58 ^b	14.94±0.37 ^b	13.37±0.31 ^b
1,000	14.86±0.57 ^a	13.39±0.30 ^a	11.36±0.37 ^a	25.45±0.45 ^a	22.79±0.99 ^a	21.16±0.86 ^a
<i>p</i> -value, %CV	<0.001, 85.4	<0.001, 90.9	<0.001, 84.3	<0.001, 90.4	<0.001, 85.8	<0.001, 89.2

ppb = parts per billion; CV = coefficient of variance; Values (mean ± SD) in same column with different lowercase superscripts are highly significantly ($p < 0.01$) different.

However, Ti was not found in the grains of rice subjected to any treatment, revealing that TNPs could not reach rice grains. Since the usage of TNPs in food is under increasing scrutiny, especially in Europe (Bucher et al., 2024), the lack of Ti in the rice grains in the current experiments should help to ensure that current TNP application methods will remain viable under future TNP regulations.

Different responses to TNPs were observed in the current work compared to Theerak et al. (2023) and Theerak (2024) where the TNPs were used only in seed submersion. Rice height in both the current and earlier studies was impacted

by TNPs; however, in the earlier study, the use of TNPs above 10 mg/L provided no additional benefits, while in the current work, the TNP concentration at 1,000 mg/L led to the greatest plant height for all TNP sizes. The chlorophyll contents of leaves on day 120, as measured by SPAD indices, were not influenced by TNP treatments in the earlier work; however, in the current work, the use of the TNPs significantly improved the contents. More strikingly, in the earlier work, the TNP exposure did not improve the number of tillers per hill, and rice plants under all treatment did not reach flowering stages nor provide any grains. This discrepancy in

the effects showed that using TNPs for seed submersion and soil amendment was more beneficial than using them for seed submersion alone. While the earlier work revealed that seed submersion could improve photosynthesis in the seedlings of both rice cultivars, this effect only lasted for 30 d. Thus, to further enhance the photosynthesis in rice, the addition of TNPs to the soil should be conducted before day 30. In the current work, the addition occurred on day 25, with this timely TNP usage being sufficient to enhance rice growth and yield further.

The positive effects of TNP treatments in the current work were in general agreement with other studies, with some slight differences due to diverging experimental conditions. In a study by Zahra et al. (2017), soil amendment with 20 nm TNP suspensions with TNP concentrations up to 750 ppm enhanced both plant height and weight, which was in agreement with the current work. Notably, Zahra et al. (2017) also found that the TNP treatment with concentrations above 25 ppm did not necessarily provide additional benefits to rice weight, which matched well with the current results. The effects of TNP addition shown in both studies suggested that there were processes other than photosynthesis that were not influenced by the TNP treatments but were limiting factors for rice growth, flowering and grain filling. These processes could include plant transpiration (Peng et al., 2023) and carbohydrate metabolism (Hong et al., 2021). Because in both studies no additional fertilizers were added, these processes might be impeded and become limiting factors, leading to the diminished effects of TNP treatment on growth and yield parameters. Therefore, it is important to further study and optimize the use of TNPs, along with other fertilizers, so that all mechanisms responsible for plant growth and yield are enhanced. For example, Ullah et al. (2020) found that the use of TNPs along with phosphorus fertilizer improved wheat growth and yield more than the use of TNPs alone. Studies such as theirs on rice would promote more effective use of TNPs.

The study by Rafique et al. (2018) also investigated the use of 20 nm TNPs to amend soil for Galaxy 2013 rice cultivation. Those authors added TNPs in the form of powder rather than a suspension. Based on a comparison of soil mass, the TNP treatment in the current study with the suspension of 1,000 mg/L was equivalent to the addition of 40 ppm of TNP powder in the work by Rafique et al. (2018). Similar to the current experiment, their study found that the TNP treatment improved rice height and chlorophyll content. This result supported the current findings regarding the effects of TNPs on rice growth and the underlying mechanism of TNPs.

Rafique et al. (2018) also explored the addition of TNP powder at a concentration of 60 ppm, which was found to be even more beneficial to rice growth and photosynthesis, suggesting that a TNP suspension treatment above the maximum applied in the current experiment (1,000 mg/L) might provide better effects, which should be explored in future work. However, in the study by Xu et al. (2021), TNPs with a wide size distribution (20–100 nm) in powder form were added to the soil in which Wuyunjing 23 rice was grown. The concentration of TNPs was 200 ppm, which was more than eight times the maximum (1,000 mg/L) in the current treatment. The treatment in Xu et al. (2021) reduced the chlorophyll content of rice and grain weight, showing that excessive use of TNPs could become toxic to rice and that the toxicity of TNPs was related to the chlorophyll content. Thus, the link between TNPs and photosynthesis in rice identified in the current work was confirmed by Xu et al. (2021).

The positive links between TNP treatment, rice growth and yield, and chlorophyll enhancement (shown in [Figs. S1](#) and [S2](#)) in the current work were confirmed by other works; however, the underlying mechanism was still not conclusive. Nonetheless, based on the results from the current study, it could be surmised that when TNPs were transported into the cytoplasm of rice cells, the titanium ions of the TNPs enhanced electron transport in photosystem I used in photosynthesis (Cigler et al., 2010). Due to the similarity in the chemical properties of titanium (Ti^{4+} and Ti^{3+}) and iron ions (Fe^{3+} and Fe^{2+}), redox reactions between the two types of ions could enhance the activities of iron ions that are crucial components in the complexes involving in photosystem I. In addition, Ti^{4+} and Fe^{3+} ions have similar ionic radii and thus can similarly bind to the electron donor proteins used in photosystem II. Thus, Ti^{4+} from TNPs may improve rice photosynthesis via photosystem II as well. The effects of TNP size observed in the current work were consistent with the proposed explanation given by Theerak et al. (2023) and Theerak (2024). According to Tripathi et al. (2017), TNPs must be transported from soil into rice roots and then pass through several plant tissues, with each tissue having a size exclusion limit, resulting in the passage of TNPs whose size is larger than this limit being hindered, though not completely blocked. One boundary that might play an important role in limiting TNP translocation is the endodermis, where TNPs and water transport are controlled by a Casparian strip. The size exclusion limit was reported to be around 1 nm (Wang et al., 2016). Because water is also limited by a Casparian strip, the size of TNPs, not the hydrodynamic size, is a salient factor in regulating the TNP passage.

Therefore, fewer TNPs of larger sizes will be transferred into rice. This was supported by the findings from the current work, which showed that smaller TNPs accumulated in rice roots, stems and leaves. Nevertheless, once the TNPs reach the rice leaves, they must be transported into the cell cytoplasm to influence photosynthesis. This passage into the cytoplasm is mediated by water making the hydrodynamic size the deciding parameter. Therefore, TNPs with a smaller hydrodynamic size would be transported more efficiently and could influence photosynthesis to a greater extent. For this reason, the large TNPs in the current study, with the smallest hydrodynamic size, had a better impact on rice growth and yield, despite accumulating in rice tissues to a lesser degree.

In conclusion, the current work highlighted the combined use of TNPs in seed submersion and soil amendment for enhancing rice growth. The large TNPs with an average diameter of 468 nm were the most beneficial to rice growth and resulted in the least Ti accumulation. Increasing the TNP concentration above 10 ppm further improved rice height and chlorophyll content but provided no benefits to other yield parameters. The TNP treatments did not have any effects on rice yield quality. Overall, TNPs improved rice growth and yield by promoting photosynthesis in the rice; however, other metabolic processes could be limiting factors to growth, flowering and grain filling in rice, which might, in turn, hinder the positive effects of TNPs. Therefore, the combined use of the large TNPs should be recommended to improve rice growth. Future work should explore the use of TNPs accompanied by other complementing fertilizers so that rice growth and yield can be optimized.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

Professor Dr. Niphone Thaveechai and Dr. Laddawan Kunnot provided valued advice for this project. The Sukhothai Thammathirat Open University provided facilities and supplies for the experiments. The Thailand National Science and Technology Development Agency provided nanoparticle characterization and the Pathum Thani Rice Research Center and the Surin Rice Seed Center supplied rice seed samples.

References

- Bucher, G., El Hadri, H., Asensio, O., Auger, F., Barrero, J., Rosec, J.-P. 2024. Large-scale screening of E171 food additive (TiO₂) on the French market from 2018 to 2022: Occurrence and particle size distribution in various food categories. *Food Control* 155: 110102. doi.org/10.1016/j.foodcont.2023.110102
- Butt, B.Z., Naseer, I. 2020. Nanofertilizers. In: Javad, S. (Ed.). *Nanoagronomy*. Springer International Publishing. Cham, Switzerland, pp. 125–152.
- Chandel, M., Kaur, K., Sahu, B.K., Sharma, S., Panneerselvam, R., Shanmugam, V. 2022. Promise of nano-carbon to the next generation sustainable agriculture. *Carbon* 188: 461–481. doi.org/10.1016/j.carbon.2021.11.060
- Cigler, P., Olejnickova, J., Hruby, M., Csefalvay, L., Peterka, J., Kuzel, S. 2010. Interactions between iron and titanium metabolism in spinach: A chlorophyll fluorescence study in hydropony. *J. Plant Physiol.* 167:1592–1597. doi.org/10.1016/j.jplph.2010.06.021
- Debnath, K., Das, A., Das, B., Karfoma, J. 2020. TiO₂ nanoparticles enhancing germination, growth and yield of rice. *Int. Res. J. Pure Appl. Chem.* 21: 25–30. doi.org/10.9734/irjpac/2020/v21i630173
- Dola, D.B., Mannan, M.A., Sarker, U., et al. 2022. Nano-iron oxide accelerates growth, yield, and quality of Glycine max seed in water deficits. *Front. Plant Sci.* 13: 992535. doi.org/10.3389/fpls.2022.992535
- El-Moneim, D.A., Dawood, M.F.A., Moursi, Y.S., Farghaly, A.A., Afifi, M., Sallam, A. 2021. Positive and negative effects of nanoparticles on agricultural crops. *Nanotechnol. Environ. Eng.* 6: 21. doi.org/10.1007/s41204-021-00117-0
- Faraz, A., Faizan, M., Fariduddin, Q., Hayat, S. 2020. Response of Titanium Nanoparticles to plant growth: Agricultural Perspectives. In: Hayat, S., Pichtel, J., Faizan, M., Fariduddin, Q. (Eds.). *Sustainable Agriculture Reviews 41: Nanotechnology for Plant Growth and Development*. Springer International Publishing. Cham, Switzerland, pp. 101–110.
- Hong, W.-J., Jiang, X., Choi, S.-H., Kim, Y.-J., Kim, S.-T., Jeon, J.-S., Jung, K.-H. 2021. A systemic view of carbohydrate metabolism in rice to facilitate productivity. *Plants*. 10: 1690. doi.org/10.3390/plants10081690
- Hsu, C.-Y., Mahmoud, Z.H., Abdullaev, S., et al. 2024. Nano titanium oxide (nano-TiO₂): A review of synthesis methods, properties, and applications. *Case Stud. Chem. Environ. Eng.* 9: 100626. doi.org/10.1016/j.cscee.2024.100626
- Hussain, A., Rehman, F., Rafeeq, H., et al. 2022. *In-situ, ex-situ*, and nano-remediation strategies to treat polluted soil, water, and air – A review. *Chemosphere* 289: 133252. doi.org/10.1016/j.chemosphere.2021.133252
- Jakhar, A.M., Aziz, I., Kaleri, A.R., Hasnain, M., Haider, G., Ma, J., Abideen, Z. 2022. Nano-fertilizers: A sustainable technology for improving crop nutrition and food security. *NanoImpact* 27: 100411. doi.org/10.1016/j.impact.2022.100411
- Ji, Y., Zhou, Y., Ma, C., et al. 2017. Jointed toxicity of TiO₂ NPs and Cd to rice seedlings: NPs alleviated Cd toxicity and Cd promoted NPs uptake. *Plant Physiol. Bioch.* 110: 82–93. doi.org/10.1016/j.plaphy.2016.05.010

- Johnson, M.S., Sajeev, S., Nair, R.S. 2021. Role of nanosensors in agriculture. In: 2021 International Conference on Computational Intelligence and Knowledge Economy. Dubai, United Arab Emirates, pp. 58–63.
- Kale, S.K., Parishwad, G.V., Patil, A.S.N.H.A.S. 2021. Emerging agriculture applications of silver nanoparticles. *ES Food Agrofor.* 3: 17–22.
- Kumar, M., Singh, Y.K., Maurya, S.K., Maurya, S.K., Maurya, D.K., Sachan, R., Gautam, M.K., Tiwari, A. 2023. Efficient use of nano-fertilizer for increasing productivity and profitability along with maintain sustainability in rice crop: A review. *Int. J. Environ. Clim.* 13: 1358–1368. doi.org/10.9734/ijec/2023/v13i102788
- Ma, H.-Y., Zhao, L., Guo, L.-H., Zhang, H., Chen, F.-J., Yu, W.-C. 2019. Roles of reactive oxygen species (ROS) in the photocatalytic degradation of pentachlorophenol and its main toxic intermediates by TiO₂/UV. *J. Hazard. Mater.* 369: 719–726. doi.org/10.1016/j.jhazmat.2019.02.080
- Mohadesi, M., Fard, M.S., Shokri, A. 2022. The application of modified nano-TiO₂ photocatalyst for wastewater treatment: A review. *Int. J. Environ. An. Ch.* 104: 2571–2592. doi.org/10.1080/03067319.2022.2064751
- Parrino, F., Palmisano, L. 2020. Titanium Dioxide (TiO₂) and Its Applications. Elsevier. Amsterdam, the Netherlands.
- Peng, C., Song, H., Zhao, Z., et al. 2023. Foliar spraying with a mixture of transpiration inhibitor-rhamnolipid reduces the Cd content in rice grains. *Sci. Total Environ.* 885: 163844. doi.org/10.1016/j.scitotenv.2023.163844
- Rafique, R., Zahra, Z., Virk, N., Shahid, M., Pinelli, E., Park, T.J., Kallerhoff, J., Arshad, M. 2018. Dose-dependent physiological responses of *Triticum aestivum* L. to soil applied TiO₂ nanoparticles: Alterations in chlorophyll content, H₂O₂ production, and genotoxicity. *Agr. Ecosyst. Environ.* 255: 95–101. doi.org/10.1016/j.agee.2017.12.010
- Rizwan, R., Ai, S., ur Rehman, M.Z., et al. 2019. Effect of foliar applications of silicon and titanium dioxide nanoparticles on growth, oxidative stress, and cadmium accumulation by rice (*Oryza sativa*). *Acta Physiol. Plant* 41: 35. doi.org/10.1007/s11738-019-2828-7
- Rodríguez-González, V., Terashima, C., Fujishima, A. 2019. Applications of photocatalytic titanium dioxide-based nanomaterials in sustainable agriculture. *J. Photoch. Photobio. C* 40: 49–67. doi.org/10.1016/j.jphotochemrev.2019.06.001
- Singh, R.P., Handa, R., Manchanda, G. 2021. Nanoparticles in sustainable agriculture: An emerging opportunity. *J. Control. Release* 329: 1234–1248. doi.org/10.1016/j.jconrel.2020.10.051
- Theerak, W. 2024. Use of titanium dioxide nanoparticles with varying sizes and concentrations by seed submersion in production of photo-sensitive and non-photo-sensitive rice cultivars. In: Proceeding of the 12th Muban Chombueng Rajabhat National Conference. Rachaburi, Thailand, pp. 14–29.
- Theerak, W., Dittthakit, P., Puttamuk, T., Chuawong, P. 2023. Effects of size and dose of titanium dioxide on the early development of rice exposed to nanoparticle suspensions. *J. Biosyst. Eng.* 48: 412–427. doi.org/10.1007/s42853-023-00201-0
- Tian, Q., Zhang, Z., Yang, L., Hirano, S. 2015. Fabrication of mesoporous titanium dioxide/tin dioxide/carbon hollow microspheres as high performance anode for lithium-ion batteries. *J. Power Sources* 279: 528–532. doi.org/10.1016/j.jpowsour.2015.01.048
- Tripathi, D.K., Shweta, Singh, S., et al. 2017. An overview on manufactured nanoparticles in plants: Uptake, translocation, accumulation and phytotoxicity. *Plant Physiol. Bioch.* 110: 2–12. doi.org/10.1016/j.plaphy.2016.07.030
- Ullah, S., Adeel, M., Zain, M., et al. 2020. Physiological and biochemical response of wheat (*Triticum aestivum*) to TiO₂ nanoparticles in phosphorous amended soil: A full life cycle study. *J. Environ Manage.* 263: 110365. doi.org/10.1016/j.jenvman.2020.110365
- Usman, M., Farooq, M., Wakeel, A., Nawaz, A., Cheema, S.A., Rehman, H.u., Ashraf, I., Sanaullah, M. 2020. Nanotechnology in agriculture: Current status, challenges and future opportunities. *Sci. Total Environ.* 721: 137778. doi.org/10.1016/j.scitotenv.2020.137778
- Verma, K.K., Song, X.-P., Joshi, A., et al. 2022. Nanofertilizer possibilities for healthy soil, water, and food in future: An overview. *Front. Plant Sci.* 13: 865048. doi.org/10.3389/fpls.2022.865048
- Waani, S.P.T., Irum, S., Gul, I., et al. 2021. TiO₂ nanoparticles dose, application method and phosphorous levels influence genotoxicity in Rice (*Oryza sativa* L.), soil enzymatic activities and plant growth. *Ecotox. Environ. Safe.* 213: 111977. doi.org/10.1016/j.ecoenv.2021.111977
- Wang, D., Saleh, N.B., Byro, A., et al. 2022. Nano-enabled pesticides for sustainable agriculture and global food security. *Nat. Nanotechnol.* 17: 347–360. doi.org/10.1038/s41565-022-01082-8
- Wang, P., Lombi, E., Zhao, F.-J., Kopittke, P.M. 2016. Nanotechnology: A new opportunity in plant sciences. *Trends Plant Sci.* 21: 699–712. doi.org/10.1016/j.tplants.2016.04.005
- Wang, Y., Deng, C., Cota-Ruiz, K., et al. 2020. Improvement of nutrient elements and allicin content in green onion (*Allium fistulosum*) plants exposed to CuO nanoparticles. *Sci. Total Environ.* 725: 138387. doi.org/10.1016/j.scitotenv.2020.138387
- Wang, Y., Deng, C., Rawat, S., Cota-Ruiz, K., Medina-Velo, I., Gardea-Torresdey, J.L. 2021. Evaluation of the effects of nanomaterials on rice (*Oryza sativa* L.) responses: Underlining the benefits of nanotechnology for agricultural applications. *ACS Agric. Sci. Technol.* 1: 44–54. doi.org/10.1021/acsagritech.1c00030
- Xu, M., Mao, L., Du, W., Guo, H., Yin, Y. 2021. Divergence in response of japonica and hybrid rice to titanium dioxide nanoparticles. *J. Soil. Sediment.* 21: 1688–1697. doi.org/10.1007/s11368-021-02890-6
- Zahra, Z., Waseem, N., Zahra, R., Lee, H., Badshah, M.A., Mehmood, A., Choi, H.-K., Arshad, M. 2017. Growth and metabolic responses of rice (*Oryza sativa* L.) cultivated in phosphorus-deficient soil amended with TiO₂ nanoparticles. *J. Agric. Food Chem.* 65: 5598–5606. doi.org/10.1021/acs.jafc.7b01843
- Zhou, X.-Q., Hayat, Z., Zhang, D.-D., Li, M.-Y., Hu, S., Wu, Q., Cao, Y.-F., Yuan, Y. 2023. Zinc oxide nanoparticles: Synthesis, characterization, modification, and applications in food and agriculture. *Processes* 11: 1193. doi.org/10.3390/pr11041193