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Integrated Application of Compost, ZnO Nanoparticles, and NPK Fertiliser in Pot Paddy Cultivation on Inceptisol Enhance Nutrient Use Efficiency and Grain Yield

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ABSTRACT

The integration of technology and innovative practices has been created to address the adverse effects of synthetic fertilisers on agroecosystems, aiming to pinpoint sustainability constraints and enhance agricultural production systems, particularly in rice farming. This current study aimed to determine the impacts of the combined use of compost powder, ZnO nanoparticles (ZnO-NPs), and NPK fertiliser on yield, nutrient use efficiency, and grain yield of paddy. A greenhouse experiment with Randomised Block Design was used to test the effectiveness of nine treatments, namely P0 (no fertiliser), P1 (NPK fertiliser), P2 (300 g compost powder), P3 (P2+ ZnO-NPs 50 mgkg^{-1} compost), P4 (P2+ZnO-NPs100 mgkg^{-1} compost), P5 (P2+ ZnO-NPs 150 mgkg^{-1} compost), P6 (P3+½NPK), P7 (P4+½NPK), P8 (P5+½NPK). Each treatment had five replications. The treatment P7 (compost + ZnO NPs 100 mg kg^{-1} + ½ NPK) showed higher N, P, K, and Zn uptake than the NPK treatment. Although the differences were not statistically significant, the results indicate comparable nutrient uptake efficiency. This treatment also had higher dry grain weight per hill and per box (80cm × 60cm × 30cm dimension, with six plant samples), potentially of harvested and milled grain weight, than the NPK treatment. The Relative Agronomy Effectiveness of the P7 increased by 12% compared with the NPK treatment. The agronomic efficiency of P4 increased by 72% compared with the NPK treatment. This recent study offered new perspectives on the possibilities of utilising nanoparticles, decreasing the chemical Fertilisers used, and enhancing the efficiency of nutrient use and grain yield for lowland rice cultivation. The findings could be confirmed in field trials.

Keywords: Compost-powder, nutrient use efficiency, paddy grain yield, ZnO-nanoparticles

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INTRODUCTION

To date, most of the increase in agricultural productivity throughout Indonesia has been carried out through conventional farming using chemical fertilisers continuously and at high rates to overcome nutrient deficiencies in the soil. The fertiliser needs of farmers in Indonesia should be 13.5 million tons per year. However, Indonesia can produce 3.5 million tons annually, and an additional 7.3 million tons are imported (Central Statistics Agency of Indonesia (CSAI, 2023). Chemical fertilisers supply nutrients to ensure ideal plant growth and yield; however, current production systems struggle to meet rising food demand without substantial fertiliser application (Zhang et al., 2015). However, applying chemical fertilisers negatively impacts soil fertility because these inorganic fertilisers cannot replenish soil humus and, therefore, cannot restore soil fertility in the long term (Purwanto & Alam, 2020). Due to global limitations on available farmland and water resources, optimising mineral fertiliser use is crucial for increasing food production, supporting a growing population, and driving economic progress. Yet, sustainability in agriculture faces obstacles like inefficient nutrient absorption and environmental concerns linked to chemical fertiliser application. However, excessive fertiliser use raises expenses, diminishing farmers' profitability. High rates of conventional fertiliser release that surpass the pace at which plants absorb nutrients and/or transform fertiliser into forms unavailable to plants are the usual causes of low nutrient utilisation efficiency (Chhipa, 2017).

Utilising organic fertilisers and minimising inorganic fertiliser application is an effective strategy for preserving soil health, boosting plant productivity, and improving fertiliser efficiency in farming systems (Lal & Stewart, 2019; Vanlauwe et al., 2015). The use of compost and chemical fertilisers is also the best practice of best practices of an integrated nutrient management strategy that has been extensively studied for its potential to increase agricultural output and sustainably improve Nutrient Use Efficiency (NUE) (Oyetunji et al., 2022). However, using organic fertilisers such as compost derived from organic residues often faces the constraints of slow nutrient release and low nutrient content. Organic fertilisers are not soluble in water, and their nutrients are dispersed into the soil more slowly than conventional water-soluble fertilisers, which are readily dispersed as the fertiliser dissolves (Shaji et al., 2021). Therefore, a growing interest is in developing new fertiliser technologies to maximise efficiency (Van Eerd et al., 2018).

The application of nanotechnology in fertiliser development represents a promising strategy to enhance global food crop production sustainably in the context of climate change (Feregrino-Perez et al., 2018; Pradhan & Mailapalli, 2017; Raliya et al., 2017). Nevertheless, the use of nanomaterials must be carefully managed to prevent adverse effects on plant metabolic processes (Mirbakhsh, 2023; Tarafdar et al., 2015). Nanomaterials such as ZnO, FeO, and ZnFeCu-oxide can significantly enhance seed germination, support plant growth, and elevate crop yield quality in several species, including peanut, soybean, wheat, onion, spinach, tomato, potato, and mustard greens (El-Saadony et al., 2021; Pradhan et al., 2010; Shojaei et al., 2019). These improvements are attributed to the enhanced nutrient efficiency resulting from nanoparticles' high surface area and active penetration capabilities (Mirbakhsh, 2023). However, research on the application of nanoparticles in rice cultivation remains limited despite rice's strategic and economic importance as a staple food in Indonesia. Therefore, this study investigates the effect of nanoparticle-enhanced compost on the nitrogen use efficiency (NUE) of rice cultivation. The gradual development of nanomaterials improves NUE while lowering N losses and environmental pollution (Panel, 2015; Preetha & Balakrishnan, 2017). Nitrogen use efficiency (NUE) computes the conversion of nitrogen inputs into agricultural products and looks at nitrogen losses in the environment (Norton et al., 2015).

Adding nanoparticles to powdered compost is expected to improve nutrient use efficiency and decrease dependence on chemical fertilisers within rice cultivation systems. In particular, zinc oxide (ZnO) nanoparticles have attracted considerable attention due to their beneficial effects on plant growth and health. Several previous research studies have demonstrated that applying ZnO nanoparticles at optimal doses can significantly stimulate plant development. Zinc is essential for activating various plant enzymes involved in carbohydrate metabolism, maintaining cell membrane stability, facilitating protein synthesis, and regulating auxin synthesis, which collectively promote the growth and development of roots and shoots (Jolli et al., 2020). This research hypothesises that adding ZnO nanoparticles to organic fertilisers can increase the efficiency of inorganic fertiliser use. Therefore, this current research is designed to evaluate the integrated effects of compost powder, ZnO nanoparticles, and the reduction of NPK fertiliser dosage on optimising nutrient use and enhancing grain yield in paddy cultivation. Through this approach, it is expected that innovative solutions can be found to increase rice productivity sustainably and efficiently.

MATERIALS AND METHODS

Experimental Site and Design

A greenhouse experiment was conducted at the field laboratory, the Faculty of Agriculture, Universitas Islam Malang, East Java Province, Indonesia, located at coordinates 7 ° 56 ’ 15” S and 112 ° 36 ’ 21” E with an elevation of 510 m above sea level. This study tested nine treatments using a randomised block design, consisting of P0 (control, no fertiliser), P1 (NPK fertiliser), P2 (300 g compost powder), P3 (P2 + ZnO-NPs at 50 mg kg^{-1} compost), P4 (P2+ZnO-NPs at 100 mg kg^{-1} compost), P5 (P2+ZnO-NPs at 150 mg kg^{-1} compost), P6 (P3+½ NPK), P7 (P4+½ NPK), and P8 (P5+½ NPK). Each treatment was replicated five times. The planting pot used was a wooden box with dimensions 80 cm × 60 cm × 30 cm. To achieve a soil depth of 25 cm in the box, 100 kg of Inceptisol soil is required. The soil weight for each pot was calculated using the bulk density method (1.25 g cm^{-3}). Inceptisol soil samples were taken from agricultural land at 0-30 cm depth using a stainless-steel auger (Blake & Hartge, 1986). Six rice seedlings aged 21 days after sowing were planted in a wooden box with a planting distance of 20 cm × 20 cm. The total number of wooden boxes was 45, and the total plant population was 270.

Making of Powder Compost and ZnO Nanoparticles

Composting was carried out in the integrated laboratory of the Faculty of Agriculture, Universitas Islam Malang, where the compost material was first prepared in a composting bin. Cow dung, goat dung, cocopeat, spent mushroom waste, rice husk biochar, and rice bran were the compost materials utilised in a 3:1:3:3:3:3:1 ratio. The organic matter was first dried and ground to speed up decomposition. Then, it was evenly blended with a hoe to ensure uniformity. Afterwards, a decomposer, activated at a concentration of 2.5 litres per 500 kg of compost, was added to the composting container. Next, after diluting the decomposer solution with water, it was equally distributed across the organic materials' surface until the materials' moisture content reached 40%. Composting lasted 30 days under aerobic conditions, and maturity was determined by C/N ratio (<20) and stable temperature (Antil et al., 2014; Kumar et al., 2010). Compost production was replicated three times. In addition, to achieve compost powder, the produced compost was dried to 10% moisture and pulverised using a grinder mill. The chemical composition of compost powder is presented in Table 1.

Table 1
Chemical composition of compost powder

Parameter	Results	Methods
pH	7.3	Electrometry
C-Organic (%)	12.96	Walkley and Black
Organic matter (%)	16.46	
N-Total (%)	1.23	Kjeldahl
C/N ratio	10.54	-
P-Total (%)	0.35	Wet Oxidation with HNO_3 and $HClO_4$
K-Total (%)	0.68	
Ca-Total (%)	1.85	
Mg-Total (%)	0.66	
Fe-Total (ppm)	7333.70	
Zn-Total (ppm)	107.80	
S-SO_4 (ppm)	1859.13	

The ZnO-NPs utilised in this recent study were acquired from NanoTech Indonesia Global Co., Ltd., located in Serpong, Indonesia, and obtained using a top-down approach. A bulk ZnO material that has been oven-treated at a temperature of 100 °C was reduced in size mechanically using Planetary Ball Milling, which contains four milling jars containing balls. The machine was turned on at 400 rpm for 12 hours until nanometer-scale ZnO was produced. These nanoparticles were identified as spherical, with an average size of roughly 100 nm, based on PSA characterisation (Figure 1) (Ealia & Saravanakumar, 2017). The ZnO-NPs solids were weighed at 15 mg, 30 mg, and 45 mg and added to 300 g of powder compost using a dry mixer. The weighing of ZnO-NPs and powder compost was carried out using several predetermined treatments.

Soil Properties

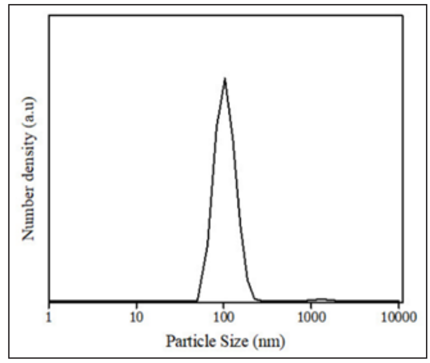

Figure 1. Particle size distribution of ZnO nanoparticles

The agricultural soil samples obtained from 0-30 cm depth were air-dried, ground, and sieved through a 2 mm mesh, then blended for consistency. The soil type was an Inceptisol. The soil characteristic was Sandy Clay Loam, covering 31.6% clay, 22.8% silt, and 45.6% sand. The soil was very low in organic carbon (0,53%), with pH 5.9 (low), low in total N (0.13%), low in phosphorus (15.37 mg kg^{-1}), and moderate in exchangeable K (0.33 me.100 g^{-1} soil), high in Capacity Exchangeable Cation (CEC) (25.99 me.100 g^{-1}), very low in Electrical Conductivity (EC) (978 µS cm^{-1}), moderate in zinc (0.14 mg kg^{-1}), and very high in Basic Saturation (73%).

Agronomic Management System

The 100 kg of air-dried soil samples were flooded and made into mud in the planting box. Application of ZnO-NPs enhanced compost powder was carried out one day before transplanting. This current research involved Inpari 32 variety rice seed, which is frequently cultivated in East Java, Indonesia. This rice variety has a growth cycle spanning 125 days. The seeds were sown on April 18, 2024. The seedlings were transplanted after 25 days of growth into the growing block containing muddy soil with a planting distance of 20 cm × 20 cm at a density of 6 hills per box, and each hill contained three rice seedlings (Figure 2). One week after planting (WAP), inorganic fertilisers were applied following the recommended dosage for P1 treatment, consisting of urea (100 kg ha^{-1} ≈5g per box), superphosphate (100 kg ha^{-1} ≈ 5g per box), and KCl (50 kg ha^{-1} ≈2.5g per box). The second fertilisation, conducted at 5 WAP, involved only urea at the same dosage (100 kg ha^{-1} ≈5g per box). Treatments P5 and P6 received half the dose of NPK fertiliser, and treatment P7 received a quarter of the dose of NPK fertiliser. The plant nursery included watering into the planting box until the height of the flooding water is 1 cm. Harvesting took place on August 23, 2024.

Sampling and Data Collection

Chlorophyll and Nutrient Content of the Leaf

This study employed the Chlorophyll Meter SPAD-502 to measure chlorophyll content (Ling et al., 2011), and the Kjeldahl method was employed to determine the nitrogen (N)

Figure 2. The growth of paddy plants in a greenhouse from early growth, the maximum vegetative phase and the generative phase

content in the leaves of these crops (Okalebo et al., 2002). The wet combustion method determined the P and K using HNO_3+$HClO_4$ solvent, a Flame photometer for K content, and a UV-spectrophotometer for P content. The Zn content was controlled using an Atomic Absorption Spectrophotometer (Kalra, 1997). Then, leaf nutrient content was assessed 12 weeks after planting (WAP). Nutrient uptake was calculated from the leaf nutrient content multiplied by the plants' total dry weight per hill.

Yield and Yield Components

At maturity, the paddy plant from each box was harvested to determine the paddy plant's total fresh and dry weight. The panicles were manually cut and threshed to determine the grain yield per hill. The number of panicles and the weight of the panicle per hill were determined by calculating the average number of panicles from 6 rice plants per box. Then, the number of grains per panicle was calculated.

Grain Quality

Following harvest, the grain from each box was sun-dried and stored at room temperature for one week to prepare for grain quality analysis. A 100 g grain sample was put into a 90% alcohol solution to determine the weight of the filled and empty grain. Furthermore, the grain was also measured for dry harvest water content by oven-drying at 70 °C for 2 × 24 hours.

Measurement of Nitrogen Use Efficiency

There are some indices of nutrient use efficiency, their calculation using the difference method as follows:

1. RE = Apparent crop recovery efficiency of applied nutrient (kg increase in N uptake per kg N applied)
2. PE = Physiological efficiency of applied N (kg yield increase per kg increase in N uptake from fertiliser)
3. IE = Internal utilisation efficiency of a nutrient (kg yield per kg nutrient uptake)
4. AE = Agronomic efficiency of applied nutrient (kg yield increase per kg nutrient applied) (Dobermann, 2007)

Statistical Analysis

The gathered data were analysed using one-way ANOVA at a 5% significance level in SPSS Statistics version 26.0. If the variance analysis indicated a significant effect, the Tukey test was applied at the same significance level to determine the differences among treatment means.

RESULTS AND DISCUSSION

Chlorophyll Content and Nutrient Uptake

The variance analysis (ANOVA) results showed that the tested treatments significantly affected chlorophyll content and nutrient uptake. The integrated application of compost powder, ZnO-NPs, and NPK fertiliser positively impacted the chlorophyll content compared to the control (P0) and compost alone (P2). The P7 treatment of compost powder + ZnO-NPs of 100 mg kg^{-1} compost powder +½ NPK fertiliser in the cultivation of rice increased the chlorophyll content (SPAD value). However, the P7 treatment was not significantly different from the inorganic fertiliser treatment (P1) (Figure 3A).

Increasing the concentration of ZnO-NPs by more than 100 mg kg^{-1}, such as in P5 and P8 treatments, decreased the chlorophyll content (Figure 3A). ZnO-NPs act as a zinc (Zn) source, which is important for various plant physiological processes, such as chlorophyll synthesis and enzyme activation. The results observed in this current study align with those reported by Skiba et al. (2021), who noted that *Pisum sativum* L. showed a decrease in chlorophyll levels, expressed in SPAD units, when cultivated in soil supplemented by ZnO-NPs at concentrations above 100 mg kg^{-1}. Mukherjee et al. (2014) and Küpper et al. (1996) stated that this decrease was attributed to the Mg substitution by Zn. It results from the substitution of the Mg atoms at chlorophyll centers by Zn, which finally hampers the photosynthesis process. Zinc is an essential microelement required in small amounts

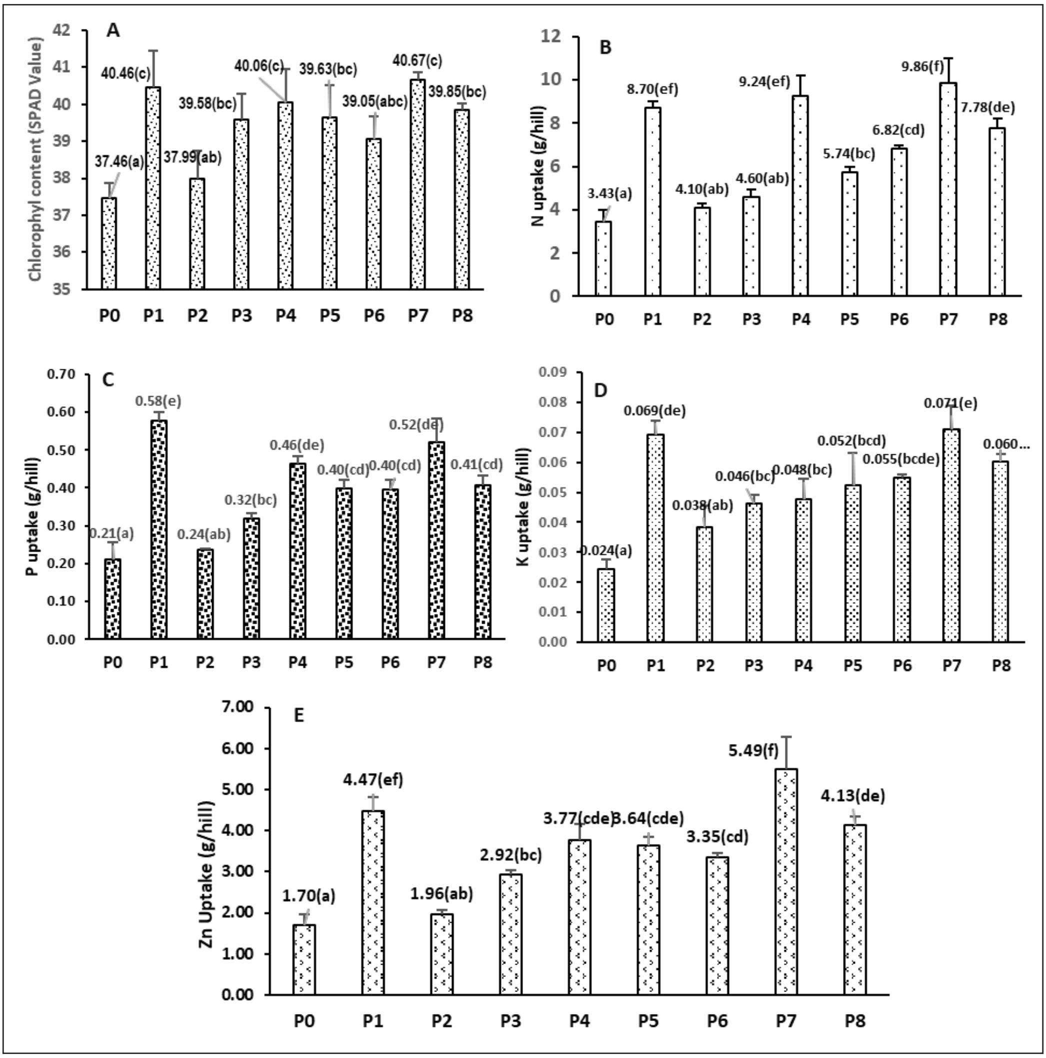

Figure 3. Chlorophyll content (A), N (B), P (C), K (D), and Zn uptake (E) of each treatment compared to control (no fertiliser, P0), NPK fertiliser (P1), and compost powder alone (P2) based on the results of Tukey test (p<0.05). Remark: HSD 5% =2.05 (A); 1.77 (B); 0.09; (C); 0.017 (D); 1.07 (E)

but significantly affects plant growth (Ayyar & Appavoo, 2017; Subramanian et al., 2014; Suganya et al., 2020).

The P4 treatment of compost powder+ZnO-NPs 100 mg $kg^{-1,}$ and P7 of compost powder+ ZnO-NPs 100 mg kg^{-1} + ½ NPK had high N and P uptake and was not significantly different from the NPK fertiliser treatment. This treatment of compost powder+ZnO-NPs 50-150 mg kg^{-1} +½ NPK (P6-P8) provided similar K uptake as the NPK treatment (Figure 3B-D). The highest Zn uptake was found in the P7 treatment of compost powder+ZnO-

NPs 100 mg kg^{-1} +½ NPK, but not significantly different from the NPK fertiliser treatment (Figure 3E). The macro and micro nutrient content of the soil samples used in this study was low to moderate, thus providing a positive response to the application of fertiliser and compost, as well as ZnO-NPs. This result showed that the addition of ZnO-NPs in compost not only functions as a more bioavailable source of zinc but also affects the absorption of other macro and micronutrients in rice plants, so that rice plant growth is better (Yang et al., 2021). ZnO-NPs have a wider specific surface, allowing the release of Zn gradually and efficiently so that plant roots can take it up (Arora et al., 2014). Plant physiology is altered by the nanoparticles in several ways, resulting in modifications at the cellular, organ, and individual plant levels (Dhiman et al., 2021; Marchiol et al., 2019; Marslin et al., 2017; Rizwan et al., 2017). Specifically, nanoparticles may either help or hinder photosynthesis, the vital process that produces bioenergy (Faizan et al., 2020; Kalaji et al., 2017; Tighe-Neira et al., 2018; Wang et al., 2018; Zhao et al., 2014). Increasing the concentration of ZnO-Nanoparticles to more than 100 mg kg^{-1} decreased the nutrient uptake of N, P, K, and Zn in leaves (Figure 3B-E). This is likely due to the effects of excess Zn, but is still not toxic to plants (Kaur & Garg, 2021).

Paddy Yield and Nutrient Utilisation Efficiency

The results of the analysis of variance (ANOVA) established that the tested treatments significantly affected the parameters of rice yield, including the fresh weight and dry weight of plant biomass, number of panicles per hill, number of grains per hill, weight of panicles per hill, weight per individual panicle, dry weight of grains per hill, dry weight of grains per box, and potential production of grains per hectare and Nutrient Utilisation Efficiency. The results of this study showed that all treatments tested gave significant differences based on the 5% Tukey test ($P<0.05$) in the parameters of rice yield (Table 2 and 3).

The P7 treatment of compost powder+ZnO-NPs100 mg kg^{-1} +½ NPK had a high rice yield component and was equal to the results of the NPK treatment statistically. This treatment had the same fresh and dry weight of biomass, number of panicles per hill as the NPK fertiliser treatment. The treatments of integrated compos powder+100-150 mg kg^{-1} ZnO-NPs+NPK fertiliser had a higher number of grains per panicle than NPK treatment (P1) and compost powder alone (Table 2), and potential yield per hectare compared to the NPK treatment and other treatments. Therefore, this treatment has the highest Relative Agronomy Effectiveness (RAE value) of 112% (Table 3; Figure 4).

This study showed that combining compost and ZnO nanoparticles can provide better results than a single application of compost. Compost supplies organic material that strengthens soil structure and boosts microbial processes, while ZnO nanoparticles, as a source of microelements, can improve plant mineral nutrition. This is due to increased nutrient uptake and better photosynthetic efficiency, which contribute to greater biomass

Table 2

Fresh and dry weight of biomass, number of panicles per hill, and number of grains per panicle of rice of each treatment compared to control (no fertiliser, P0), NPK treatment (P1), and compost alone (P2)

Treatments	**Fresh weight of biomass (g)**		**Dry weight of biomass (g)**		**Number of panicles per hill**		**Number of grains per panicle**	
P0	214.28±50.49	a	62.15±9.88	a	24.93±0.81	a	115.87±3.98	a
P1	353.01±14.89	c	98.18±4.79	e	30.30±1.31	bc	119.96±12.33	a
P2	231.94±30.84	ab	65.82±4.76	ab	28.93±0.81	b	116.49±2.44	a
P3	231.54±32.24	ab	70.39±4.37	abc	30.30±0.69	bc	126.49±2.44	ab
P4	260.51±29.71	ab	79.31±2.91	bcd	29.70±0.40	bc	132.98±12.88	ab
P5	271.51±10.09	ab	80.25±6.95	cd	28.93±0.29	b	137.84±12.41	ab
P6	260.47±41.12	ab	78.17±2.85	bcd	29.30±0.79	bc	133.55±6.16	ab
P7	296.54±32.35	bc	85.41±4.32	de	30.63±0.65	c	144.71±10.94	b
P8	271.99±22.56	ab	81.87±7.21	cd	30.20±1.51	bc	146.73±2.58	b
HSD 5%	73.96		13.51		1.66		23.70	

Note. Means followed by different letters in the same column are significantly different at Tukey test, $p < 0.05$

Table 3

Panicle weight per hill, dry weight of grain, and Relative Agronomy Effectiveness of each treatment compared to control (no fertiliser, P0), NPK treatment (P1), and compost alone (P2)

Treatments	**Weight of panicles per hill (g)**		**Weight per individual panicle (g)**		**Dry weight of grain per hill (g)**		**Dry weight of grain per box (g)**		**Relative Agronomy Effectiveness (RAE)**
P0	56.31±7.76	a	3.29±0.15	a	37.94±4.12	a	227.67±24.74	a	-
P1	111.06±6.63	c	3.75±0.25	abc	86.51±2.48	bc	519.07±14.29	bc	100.00
P2	67.64±4.46	ab	3.35±0.08	a	47.22±1.80	a	283.34±10.81	a	19.10
P3	66.53±4.76	ab	3.43±0.11	ab	52.82±5.68	a	316.95±34.11	a	30.64
P4	97.06±11.67	c	4.03±0.68	abc	74.75±4.92	b	448.51±29.52	b	75.79
P5	90.17±6.70	bc	4.13±0.27	abc	70.95±3.43	b	425.69±18.49	b	67.95
P6	89.40±4.21	bc	3.93±0.33	abc	72.56±8.41	b	435.35±50.48	b	71.27
P7	117.50±21.22	c	4.58±0.29	c	92.45±10.22	c	554.73±61.34	c	112.24
P8	100.84±4.23	c	4.33±0.26	bc	83.66±2.56	bc	501.96±15.39	bc	94.13
HSD 5%	28.36		0.94		16.77		99.09		

Note. Means followed by different letters in the same column are significantly different at Tukey-test, $p < 0.05$

formation and higher plant productivity. ZnO-NPs may readily release bioavailable Zn^{2+} into the soil, whereupon it may either react with soil organic matter or agglomerate and stick to soil particles, hence influencing soil microorganisms and enzymes (Liu et al., 2015; Santiago-Martín et al., 2016). This condition will greatly assist root development so that more water and nutrients from the soil will ultimately increase rice grain production.

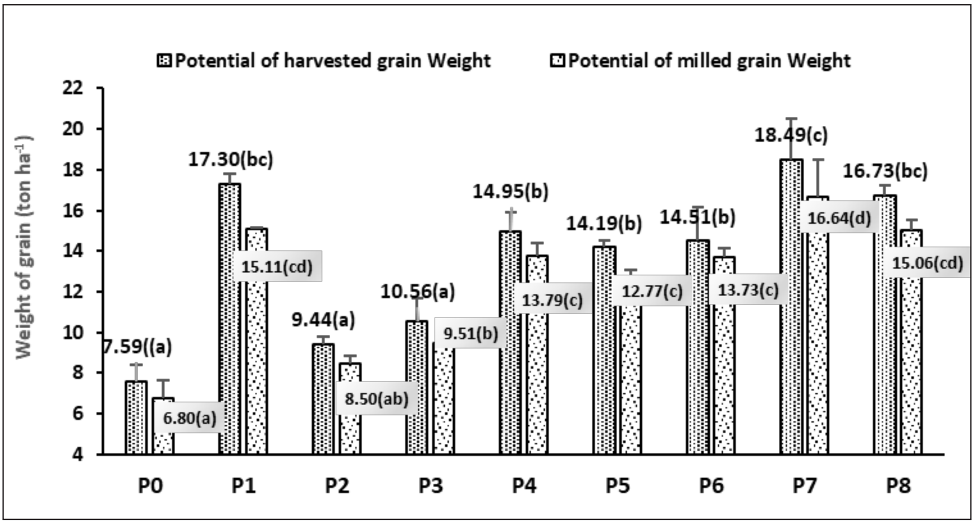

Figure 4. Potential of harvested and milled grain weight of each treatment compared to control (no fertiliser, P0), NPK treatment (P1), and compost alone (P2), based on the results of Tukey test (p<0.05). (Remark: HSD 5% =3.28; 2.52)

Based on the results of the calculation of nutrient use efficiency using the parameters of the Internal Utilisation Efficiency, the P0 treatment (no fertiliser) and the treatments of powder compost alone (P2) and compost+ZnO NPs 50-150 mg kg^{-1} (P3 and P5) provided higher efficiency than the NPK treatment (Table 4). However, quantitatively, these treatments gave low yields. Based on the results of the calculation of the Agronomic Efficiency against the control (P0), treatments P4 and P5 (compost powder+ZnO-NPs

Table 4
Internal Utilisation Efficiency (IE), Agronomic Efficiency (AE), Physiologic Efficiency (PE), and Apparent Crop Recovery Efficiency (RE) of each treatment calculated against the control (no fertiliser, P0)

Treatments	IE		AE		PE		RE	
P0	34.60±2.01	d						
P1	24.05±1.52	b	187.80±30.73	c	17.66±1.37	bcd	10.62±1.18	c
P2	32.54±0.52	d	62.39±7.18	a	21.64±6.79	cd	2.77±1.19	a
P3	29.80±0.11	c	111.42±17.52	ab	18.83±2.66	bcd	5.95±0.92	ab
P4	19.14±0.90	a	260.07±41.96	d	10.38±2.64	a	24.91±4.09	d
P5	29.70±0.14	c	246.26±44.18	d	23.28±2.04	d	10.55±1.25	c
P6	24.57±0.06	b	77.01±12.85	ab	15.21±3.11	ab	4.92±1.18	ab
P7	20.58±0.32	a	118.28±10.37	b	13.28±2.31	ab	8.73±1.44	bc
P8	23.48±0.26	b	99.52±8.50	ab	15.76±0.93	abc	6.31±0.26	ab
HSD 5%	2.43		51.44		6.17		3.99	

Note. Means followed by different letters in the same column are significantly different at Tukey-test, p <0.05

100-150 mg kg^{-1}) provided high-efficiency values in utilising nutrients in the soil and higher than the NPK treatment (P1), while the Physiologic Efficiency and Apparent Crop Recovery Efficiency of P5 treatment (compost powder+ZnO-nanoparticles 150 mg kg^{-1}) had the highest efficiency values.

Grain Quality

The variance analysis (ANOVA) results demonstrated that the tested treatments significantly affected parameters. In addition to increasing quantitative yield, the treatments of compost powder+ZnO-NPs 100-150 mg kg^{-1} compost (P4 and P5) and the treatment of compost powder+ZnO-NPs 50-100 mg kg^{-1} compost +½ NPK fertiliser (P6 and P7) improve the grain's value as measured by the percentage of weight of filled and empty grain and grain water content. The treatments had the lowest grain water content (Table 5). The treatments provided better grain quality than the NPK treatment (P2) and control (P0). This study's results align with the research of Zhang et al. (2021), which reported that applying ZnO-NPs increased grain production, dry matter accumulation, and grain quality. Zhao et al. (2014) reported that adding ZnO nanoparticles also improves the quality of cucumber plants.

Zn is an essential element in protein synthesis and formation of pollen grain (Herschfinkel et al., 2007; Mathpal et al., 2015) and enzyme activity since plant enzymes that utilise Zn as a cofactor include SOD, CA, alcohol dehydrogenase and the structural Zn-finger domains mediating DNA-binding of transcription factors and protein-protein interactions (Maret, 2009; Sinclair & Krämer, 2012). Zinc also plays a vital role in seed development, as its deficiency in plants leads to delayed maturity (Hansch & Mendel,

Table 5
Weight of empty and filled grain per 100 g, and water content of grain of each treatment compared to control (no fertiliser, P0), NPK treatment (P1), and compost alone (P2)

Treatments	Weight of empty grain per 100 grammes		Weight of filled grain per 100 grammes		Water content of grain (%)	
P0	5.49±0.22	e	94.51±0.22	a	13.49±0.55	d
P1	4.41±1.01	de	95.59±1.01	ab	15.06±0.33	e
P2	3.83±0.64	cd	96.17±0.64	bc	10.76±0.48	ab
P3	3.14±0.07	abc	96.86±0.07	cd	10.62±0.17	a
P4	2.20±0.22	ab	97.80±0.22	de	12.13±0.16	bc
P5	2.52±0.40	ab	97.48±0.40	de	11.78±0.49	abc
P6	1.23±0.12	a	97.91±0.12	e	12.72±0.61	cd
P7	2.43±0.37	ab	97.57±0.37	de	11.70±0.58	abc
P8	3.41±0.13	bcd	96.59±0.13	bcd	12.99±0.60	cd
HSD 5%	1.23		1.23		1.17	

Note. Means followed by different letters in the same column are significantly different at Tukey-test, p <0.05

2009). Therefore, the addition of ZnO nanoparticles to the compost can affect the quality of rice grain. This most likely indicates that the dry matter content in rice grains increases, which improves the quality of rice as a food source. This is because the ZnO nanoparticles contained in the compost are able to increase the synthesis of certain enzymes involved in protein metabolism, such as the enzyme RNA polymerase. Thus, Zn is a component of protein (Rudani et al., 2018). Overall, the addition of ZnO nanoparticles provides dual benefits, namely increasing the efficiency of nutrient use and increasing the yield and quality of rice plants (El-Saadony et al., 2021).

CONCLUSION

The combination of compost powder+ZnO nanoparticles 100 mg kg^{-1}+½ NPK fertiliser (P7 treatment) increased the N, P, K, and Zn uptake, biomass weight, and number of panicles per hill. This treatment also had a higher harvested and milled grain weight potential than the NPK treatment, with a yield increase of 7% compared to the NPK chemical fertiliser treatment (P1). The Relative Agronomy Effectiveness and Agronomic Efficiency of the P7 treatment increased by 12% and 72% when compared to the NPK treatment. Compost powder+ZnO-NPs 150 mg kg^{-1} treatments provided higher nutrient use efficiency than the NPK treatment. This research suggests that combining organic fertiliser and nanoparticles should be considered for sustainable rice production in paddy cultivation. However, this study was limited to a pot experiment; thus, field validation under various conditions is recommended to confirm the efficiency of ZnO NP-compost combinations.

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REFERENCES

Antil, R., Raj, D., Abdalla, N., & Inubushi, K. (2014). Physical, chemical, and biological parameters for compost maturity assessment: A review. In D. K. Maheshwari (Ed.), *Composting for sustainable agriculture: Sustainable development and biodiversity* (Vol. 3, pp. 83-101). Springer. https://doi.org/10.1007/978-3-319-08004-8_5

Arora, A. K., Devi, S., Jaswal, V. S., Singh, J., Kinger, M., & Gupta, V. D. (2014). Synthesis and characterisation of ZnO nanoparticles. *Oriental Journal of Chemistry*, *30*(4), 1671-1679. https://doi.org/10.13005/ojc/300427

Ayyar, S., & Appavoo, S. (2017). Effect of graded levels of Zn in combination with or without microbial inoculation on Zn transformation in soil, yield, and nutrient uptake by maize for red soil. *Environment & Ecology*, *35*(1), 172-176. https://environmentandecology.com

Blake, G.R., & Hartge, K.H. (1986). Bulk density. In A. Klute (Ed.), *Methods of soil analysis: Part 1 physical and mineralogical methods* (2nd ed., Vol. 5, pp. 363-375). SSSA Book Series. https://doi.org/10.2136/sssabookser5.1.2ed.c13

Central Statistics Agency of Indonesia (2023). *Fertiliser imports by major country of origin, 2017-2023*. https://www.bps.go.id/id/statistics-table

Chhipa, H. (2017). Nanofertilisers and nanopesticides for agriculture. *Environmental Chemistry Letters, 15*, 15-22. https://doi.org/10.1007/s10311-016-0600-4

Dhiman, S., Bakshi, P., Kapoor, N., Sharma, P., Kohli, S. K., Mir, B. A., & Bhardwaj, R. (2021). Nanoparticle-induced oxidative stress in plant. In V. P. Singh, S. Singh, D. K. Tripathi, S. M. Prasad, & D. K. Chauhan (Eds.), *Plant responses to nanomaterials: Nanotechnology in the life sciences* (pp. 269-313). Springer. https://doi.org/10.1007/978-3-030-36740-4_12

Dobermann, A. (2007). *Nutrient use efficiency - measurement and management* [Conference presentation]. IFA International Workshop on Fertiliser Best Management Practices, Brussels, Belgium. https://www.fertiliser.org//images/Library_Downloads/2007_IFA_FBMP%20Workshop_Brussels.pdf

Ealia, S.A.M., & Saravanakumar, M. P. (2017). A review on the classification, characterisation, synthesis of nanoparticles, and their application. *IOP Conference Series: Materials Science and Engineering*, *263*, Article 032019. https://doi.org/10.1088/1757-899X/263/3/032019

El-Saadony, M. T., ALmoshadak, A. S., Shafi, M. E., Albaqami, N. M., Saad, A. M., El-Tahan, A. M., Desoky, E. S. M., Elnahal, A. S., Almakas, A., Abd El-Mageed, T. A., & Taha, A. E., (2021). Vital roles of sustainable nano-fertilisers in improving plant quality and quantity—an updated review. *Saudi Journal of Biological Sciences*, *28*(12), 7349-7359. https://doi.org/10.1016/j.sjbs.2021.08.032

Faizan, M., Faraz, A., & Hayat, S. (2020). Effective use of zinc oxide nanoparticles through root dipping on the performance of growth, quality, photosynthesis and antioxidant system in tomato. *Journal of Plant Biochemistry and Biotechnology*, *29*, 553-567. https://doi.org/10.1007/s13562-019-00525-z

Feregrino-Perez, A. A., Magaña-López, E., Guzmán, C., & Esquivel, K. (2018). A general overview of the benefits and possible negative effects of the nanotechnology in horticulture. *Scientia Horticulturae, 238*, 126-137. https://doi.org/10.1016/j.scienta.2018.03.060

Hansch, R., & Mendel, R. R. (2009). Physiological functions of mineral micronutrients (Cu, Zn, Mn, Fe, Ni, Mo, B, Cl). *Current Opinion in Plant Biology, 12*, 259-266. https://doi.org/10.1016/j.pbi.2009.05.006

Herschfinkel, M., Silverman, W. F., & Sekler, I. (2007). The zinc sensing receptor, a link between zinc and cell signalling. *Molecular Medicine, 13*, 331-336. https://doi.org/10.2119/2006-00038.Hershfinkel

Jolli, R. B., Nayak, V. H., Boranayaka, M. B., & Latha, H. C. (2020). Effect of foliar application of zinc, boron and iron on seed yield and quality of sweet corn cv. Madhuri. *Journal of Pharmacognosy and Phytochemistry, 9*(5), 914-919. https://www.phytojournal.com/archives/2020/vol9issue5/PartM/9-2-242-285.pdf

Kalaji, M. H., Goltsev, V. N., Żuk-Gołaszewska, K., Zivcak, M., & Brestic, M. (2017). *Chlorophyll fluorescence: Understanding crop performance—basics and applications*. CRC Press. https://doi.org/10.1201/9781315153605

Kalra, Y. (1997). *Handbook of reference methods or plant analysis* (1st ed.). CRC Press. https://doi.org/10.1201/9780367802233

Kaur, H., & Garg, N. (2021). Zinc toxicity in plants: a review. *Planta, 253*(6), Article 129. https://doi.org/10.1007/s00425-021-03642-z

Kumar, M., Ou Yan, L., & Lin, J.G. (2010). Co-composting of green waste and food waste at low C/N ratio. *Waste Management 30,* 602-609. https://doi.org/10.1016/j.wasman.2009.11.023

Küpper, H., Küpper, F., & Spiller, M. (1996). Environmental relevance of heavy metal-substituted chlorophylls using the example of water plants. *Journal of Experimental Botany*, *47*(2), 259-266. https://doi.org/10.1093/jxb/47.2.259

Lal, R., & Stewart, B. A. (2019). *Soil degradation and restoration in Africa*. CRC Press.

Ling, Q., Huang, W., & Jarvis, P. (2011). Use of a SPAD-502 meter to measure leaf chlorophyll concentration in *Arabidopsis thaliana*. *Photosynthesis Research*, *107*(2), 209-214. https://doi.org/10.1007/s11120-010-9606-0

Liu, X., Wang, F., Shi, Z., Tong, R., & Shi, X (2015). Bioavailability of Zn in ZnO nanoparticle-spiked soil and the implications to maize plants. *Journal of Nanoparticle Research, 17,* Article 225. https://doi.org/10.1007/s11051-015-2989-2

Marchiol, L., Filippi, A., Adamiano, A., Degli Esposti, L., Iafisco, M., Mattiello, A., Petrussa, E., & Braidot, E. (2019). Influence of hydroxyapatite nanoparticles on germination and plant metabolism of tomato (*Solanum lycopersicum L.*): Preliminary evidence. *Agronomy, 9*(4), Article 161. https://doi.org/10.3390/agronomy9040161

Maret, W. (2009). Molecular aspects of human cellular zinc homeostasis: Redox control of zinc potentials and zinc signals. *Biometals, 22*, 149-157. https://doi.org/10.1007/s10534-008-9186-z

Marslin, G., Sheeba, C.J., & Franklin, G. (2017). Nanoparticles alter secondary metabolism in plants via ROS burst. *Frontiers in Plant Science*, *8*, 832-840. https://doi.org/10.3389/fpls.2017.00832

Mathpal, B., Srivastava, P. C., Shankhdhar, D., & Shankhdhar, S. C. (2015). Improving key enzyme activities and quality of rice under various methods of zinc application. *Physiology and Molecular Biology of Plants, 21*(4), 567-572. https://doi.org/10.1007/s12298-015-0321-3

Mirbakhsh, M. (2023). Role of nano-fertiliser in plants nutrient use efficiency (NUE): A mini-review. *Journal of Genetic Engineering and Biotechnology Research, 5*(1), 75-81. https://doi.org/10.33140/JGEBR.05.02.01

Mukherjee, A., Peralta-Videa, J. R., Bandyopadhyay, S., Rico, C. M., Zhao, L., & Gardea-Torresdey, J. L. (2014). Physiological effects of nanoparticulate ZnO in green peas (*Pisum sativum L.*) cultivated in soil. *Metallomics, 6*(1), 132-138. https://doi.org/10.1039/C3MT00064H

Norton, R., Davidson, E., & Roberts, T. (2015). Nitrogen use efficiency and nutrient performance indicators. *Global Partnership on Nutrient Management*, *14*, 1-15. http://www.nutrientchallenge.org/sites/default/files/documents

Okalebo, J.R., Gathua, K.W., & Woomer, P.L. (2002). *Laboratory methods of soil and plant analysis: A working manual* (2nd ed.). Sacred Africa.

Oyetunji, O., Bolan, N., & Hancock, G. (2022). A comprehensive review on enhancing nutrient use efficiency and productivity of broadacre (arable) crops with the combined utilisation of compost and Fertilisers. *Journal of Environmental Management, 317,* Article 115395. https://doi.org/10.1016/j.jenvman.2022.115395

Panel, E. N. E. (2015). *Nitrogen Use Efficiency (NUE) an indicator for the utilisation of nitrogen in food systems*. Wageningen University. https://www.eunep.com/wp-content/uploads/2023/12/N-ExpertPanel-NUE-Session-1.pdf

Pradhan, S., & Mailapalli, D. R. (2017). Interaction of engineered nanoparticles with the agri-environment. *Journal of Agricultural and Food Chemistry, 65* (38), 8279-8294. https://doi.org/10.1021/acs.jafc.7b02528

Pradhan, D., Sindhwani, S., & Leung, K. T. (2010). Parametric study on dimensional control of ZnO nanowalls and nanowires by electrochemical deposition. *Nanoscale Research Letters, 5*, 1727-1736. https://doi.org/10.1007/s11671-010-9702-2

Preetha, P. S., & Balakrishnan, N. (2017). A review of nano fertilisers and their use and functions in soil. *International Journal of Current Microbiology and Applied Sciences*, *6*(12), 3117-3133. https://doi.org/10.20546/ijcmas.2017.612.364

Purwanto, B.H., & Alam, S. (2020). Impact of intensive agricultural management on carbon and nitrogen dynamics in the humid tropics. *Soil Science and Plant Nutrition, 66*, 50-59. https://doi.org/10.1080/00380768.2019.1705182

Raliya, R., Saharan, V., Dimkpa, C., & Biswas, P. (2017). Nanofertiliser for precision and sustainable agriculture: Current state and future perspectives. *Journal of Agricultural and Food Chemistry, 66*, 6487-6503. https://doi.org/10.1021/acs.jafc.7b02178

Rizwan, M., Ali, S., Qayyum, M. F., Ok, Y. S., Adrees, M., Ibrahim, M., Zia-ur-Rehman, M., Farid, M., & Abbas, F. 2017. Effect of metal and metal oxide nanoparticles on growth and physiology of globally important food crops: A critical review. *Journal of Hazardous Materials*, *322*, 2-16. https://doi.org/10.1016/j.jhazmat.2016.05.061

Rudani, K., Vishal, P., & Kalavati, P. (2018). The importance of zinc in plant growth: A review. *International Research Journal of Natural and Applied Sciences*, *5*(2), 38-48. https://www.aarf.asia

Santiago-Martín, A. D., Constantin, B., Guesdon, G., Kagambega, N., Raymond, S., & Cloutier, R. G. (2016). Bioavailability of engineered nanoparticles in soil systems. *Journal of Hazardous, Toxic, and Radioactive Waste, 20*(1), B4015001. https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000263

Shaji, H., Chandran, V., & Mathew, L. (2021). Organic Fertilisers as a route to controlled release of nutrients. In *Controlled release fertilisers for sustainable agriculture* (pp. 231-245). Academic Press. https://doi.org/10.1016/B978-0-12-819555-0.00013-3

Shojaei, T. R., Salleh, M. A. M., Tabatabaei, M., Mobli, H., Aghbashlo, M., Rashid, S. A., & Tan, T. (2019). Applications of nanotechnology and carbon nanoparticles in agriculture. In S. A. Rashid, R. N. I. R. Othman, & M. Z. Hussein (Eds.), *Synthesis, technology and applications of carbon nanomaterials* (pp. 247-277). Elsevier. https://doi.org/10.1016/B978-0-12-815757-2.00011-5

Sinclair, S. A., & Krämer, U. (2012). The zinc homeostasis network of land plants. *Biochimica et Biophysica Acta (BBA)-Molecular Cell Research*, *1823*(9), 1553-1567. https://doi.org/10.1016/j.bbamcr.2012.05.016

Skiba, E., Pietrzak, M., Glińska, S., & Wolf, W. M. (2021). The combined effect of ZnO and CeO2 nanoparticles on *Pisum sativum* L.: A photosynthesis and nutrients uptake study. *Cells*, *10*(11), 3105. https://doi.org/10.3390/cells10113105

Subramanian, K. S., Bharathi, C., Gomathy, M., & Balakrishnan, N. (2014). Role of arbuscular mycorrhizal (*Glomus intraradices*) fungus inoculation on Zn nutrition in grains of field grown maize. *Australian Journal of Crop Science*, *8*, 655-665. https://www.cropj.com/subramanian_8_5_2014_655_665.pdf

Suganya, A., Saravanan, A., & Manivannan, N. (2020). Role of zinc nutrition for increasing zinc availability, uptake, yield, and quality of maize (*Zea mays* L.) grains: An overview. *Communications in Soil Science and Plant Analysis, 51*(15), 2001-2021. https://doi.org/10.1080/00103624.2020.1820030

Tarafdar, J. C., Rathore, I., & Thomas, E. (2015). Enhancing nutrient use efficiency through nano technological interventions. *Indian Journal of Fertilisers, 11*(12), 46-51. https://www.researchgate.net/profile/Esther-Thomas-4/publication/377364642

Tighe-Neira, R., Carmora, E., Recio, G., Nunes-Nesi, A., Reyes-Diaz, M., Alberdi, M., Rengel, Z., & Inostroza-Blancheteau, C. (2018). Metallic nanoparticles influence the structure and function of the photosynthetic apparatus in plants. *Plant Physiology and Biochemistry, 130*, 408-417. https://doi.org/10.1016/j.plaphy.2018.07.024

Vanlauwe, B., Descheemaeker, K., Giller, K. E., Huising, J., Merckx, R., Nziguheba, G., Wendt, J., & Zingore, S. (2015). Integrated soil fertility management in sub-Saharan Africa: Unravelling local adaptation. *Soil, 1*(1), 491-508. https://doi.org/10.5194/soil-1-491-2015

Van Eerd, L. L., Turnbull, J. J. D., Bakker, C. J., Vyn, R. J., McKeown, A. W., & Westerveld, S. M. (2018). Comparing soluble to controlled-release nitrogen Fertilisers: storage cabbage yield, profit margins, and N use efficiency. *Canadian Journal of Plant Science, 9*(4), 815-829. https://doi.org/10.1139/cjps-2017-0277

Wang, X. P., Li, Q. Q., Pei, Z. M., & Wang, S. C. (2018). Effects of zinc oxide nanoparticles on the growth, photosynthetic traits, and antioxidative enzymes in tomato plants. *Biologia Plantarum, 62*, 801-808. https://doi.org/10.1007/s10535-018-0813-4

Yang, G., Yuan, H., Ji, H., Liu, H., Zhang, Y., Wang, G., Chen, L., & Guo, Z. (2021). Effect of ZnO nanoparticles on the productivity, Zn biofortification, and nutritional quality of rice in a life cycle study. *Plant Physiology and Biochemistry, 163*, 87-94. https://doi.org/10.1016/j.plaphy.2021.03.053

Zhang, H., Wang, R., Chen, Z., Cui, P., Lu, H., Yang, Y., & Zhang, H. (2021). The effect of zinc oxide nanoparticles for enhancing rice (*Oryza sativa* L.) yield and quality. *Agriculture*, *11*(12), 1247. https://doi.org/10.3390/agriculture11121247

Zhang, X., Davidson, E. A., Mauzerall, D. L., Searchinger, T. D., Dumas, P., & Shen, Y. (2015). Managing nitrogen for sustainable development. *Nature*, *528*(7580), 51-59. https://doi.org/10.1038/nature15743

Zhao, L., Peralta-Videa, J. R., Rico, C.M., Hernandez-Viezcas, J. A., Sun, Y., Niu, G., Servin, A., Nunez, J. E., Duarte-Gardea, M., & Gardea-Torresdey, J. L. (2014). CeO_2 and ZnO nanoparticles change the nutritional qualities of cucumber (*Cucumis sativus*). *Journal of Agricultural and Food Chemistry, 62*(13), 2752-2759. https://doi.org/10.1021/jf405476u