


Utilization of Fertilizer from TiO₂ Nanoparticles and Rice Husk Waste to Improve Growth and Nutrient Uptake in Chili Plants

Rismiati Rismiati¹, Rosiman Rosiman^{1,*}, Faizal Mustapa², Irwan Irwan^{3,*} 

¹ Department of Chemistry, Faculty of Mathematics and Natural Sciences, Universitas Halu Oleo, Jl. H.E.A. Mokodompit Kampus Baru Anduonohu, Kendari 93232 – Southeast Sulawesi, Indonesia

² Department of Marine Sciences, Institut Teknologi dan Bisnis Muhammadiyah Kolaka, Kolaka 93511, Southeast Sulawesi, Indonesia

³ Department of Pharmacy, Faculty of Sciences and Technology, Institut Teknologi dan Kesehatan Avicenna, Kendari 93117, Southeast Sulawesi, Indonesia

* Correspondence: rismiatiismi94@gmail.com (R.R.); irwantrg16@gmail.com (I.I.);

Received: 11.08.2024; Accepted: 25.02.2026; Published: 30.03.2026

Abstract: This study investigates the synergistic effects of titanium dioxide (TiO₂) nanoparticles (NPs) and rice husk waste on the growth and nutrient uptake of chili plants (*Capsicum annuum*). The TiO₂ NPs were synthesized using the sol-gel method and calcined at 400°C. The crystal structure, morphology, and functional groups of the samples were investigated using X-ray diffraction (XRD), field-emission scanning electron microscopy (FESEM), and Fourier transform infrared (FTIR) spectroscopy. The experimental design involved applying five different treatments to chili plants: control, NPK fertilizer, rice husk, TiO₂ NPs, and a TiO₂-rice husk. Growth parameters were also investigated, including plant height, stem diameter, and leaf number, measured over several weeks. XRD analysis confirmed the presence of anatase TiO₂ with high purity, enhancing nutrient uptake. FESEM revealed the spherical morphology of the TiO₂ NPs with a uniform size distribution, while elemental composition analysis confirmed high purity. FTIR analysis indicated the presence of hydroxyl groups, carbonyl groups, and the Ti–O–Ti bonds characteristic of anatase TiO₂. The results revealed that the combination of TiO₂ NPs and rice husk significantly enhanced plant growth compared to the control and individual treatments. These findings suggest that the use of TiO₂ NPs and rice husk waste in nano-fertilizers can enhance sustainable agricultural practices by optimizing nutrient delivery and improving soil health.

Keywords: nanoparticle TiO₂; rice husk; sol-gel; fertilizer; chili plant.

© 2026 by the authors. This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. The authors retain copyright of their work, and no permission is required from the authors or the publisher to reuse or distribute this article, as long as proper attribution is given to the original source.

1. Introduction

Modern agriculture has increasingly turned to innovative technologies to address the challenges of sustainable food production. In modern agriculture, using nanoparticles (NPs) has emerged as a promising innovation to enhance crop productivity and sustainability. Among these innovations, the application of NPs in agriculture has attracted significant interest due to their potential to enhance crop productivity, improve nutrient use efficiency, and mitigate environmental impacts [1,2]. Nano fertilizers, in particular, represent a cutting-edge approach that has demonstrated the ability to optimize nutrient delivery, minimize nutrient loss, and

promote plant growth and yield [3]. Unlike conventional fertilizers, which often suffer from inefficiencies such as leaching and volatilization, nano fertilizers are engineered to deliver nutrients more effectively, thereby improving plant uptake and utilization [4,5].

Recently, a wide range of nanoparticles such as copper oxide (CuO) [6], zinc oxide (ZnO) [7], nickel oxide (NiO) [8], cerium dioxide (CeO₂) [9], silica dioxide (SiO₂) [10], aluminum dioxide (Al₂O₃) [11], magnetite (Fe₃O₄) [12], titanium dioxide (TiO₂) [13], have been investigated for their potential to enhance plant growth and mitigate stress in various organisms such as plants. These nanoparticles have shown promising results in enhancing plant growth, improving stress tolerance, and promoting overall plant health. In particular, titanium dioxide (TiO₂) nanoparticles have been extensively studied for their photocatalytic properties and for their ability to improve nutrient absorption and photosynthetic efficiency in plants [14–16].

TiO₂ NPs have been observed to elicit a significant impact on the morphological, physiological, and biochemical characteristics of some plant species. For example, Zahra *et al.* [17] reported that applying TiO₂ NPs to rice (*Oryza sativa* L.) could raise their glycerol, amino acid, and palmitic acid contents, which in turn caused a 14.5% increase in shoot length. Bakshi *et al.* reported that Nano-TiO₂ enhanced tomato plant development without altering biochemical reactions, except for a 43% drop in leaf tannin concentration [18]. Sheikhalipour *et al.* [19] reported mitigation of abiotic stresses by TiO₂ NP application in Stevia (*Stevia rebaudiana* Bertoni) plants, improving enzyme activities, proline content, antioxidant capacity, and secondary metabolite levels. Therefore, TiO₂ may be regarded as a plant stimulant that triggers several defense systems that help plants tolerate a variety of abiotic stresses. These characteristics make TiO₂ an attractive candidate for use in nano fertilizers aimed at boosting crop yield and quality.

Agricultural waste materials, such as rice husk, have attracted attention as valuable resources for improving soil health and providing slow-release nutrients. Rice husk is primarily composed of organic compounds like cellulose, lignin, and hemicellulose, along with inorganic components, particularly silica (SiO₂), which accounts for approximately 15-20% of its composition [20]. The high silica content renders rice husk an attractive resource for various agricultural applications, including its use as a soil amendment and as a component in nanofertilizers [21]. Rice husk waste has been recognized for its potential to improve soil properties, increase water retention, and enhance nutrient availability when properly processed. Specifically, the silica content in rice husk can be advantageous for crops like chili (*Capsicum annuum*), as silicon plays a crucial role in enhancing plant resilience to biotic and abiotic stresses, including pest attacks, diseases, and environmental factors such as drought and salinity. Silicon also strengthens cell walls, improves plant structure, and promotes more efficient water and nutrient uptake [22,23].

In this work, we investigate the utilization of rice husk waste as a component in nano-fertilizers, particularly in combination with TiO₂ nanoparticles, to enhance the growth and nutrient uptake of chili plants. By focusing on the synergistic effects of rice husk and nanomaterials, this research aims to develop a sustainable, efficient approach to enhancing crop productivity in chili cultivation. Through this approach, we seek to capitalize on the unique properties of both rice husk-derived silica, known for its role in strengthening plant structure and mitigating stress factors, and TiO₂ nanoparticles, which are recognized for their photocatalytic and growth-promoting effects, to develop an eco-friendly solution that not only

supports sustainable agricultural practices but also offers a means of improving the efficiency and long-term viability of chili cultivation systems.

2. Materials and Methods

2.1. Preparation of TiO_2 nanoparticle.

TiO_2 nanoparticles were synthesized using the sol-gel method, referring to the study conducted by Maulidiyah *et al* [24]. In brief, the first solution contained 4 mL of titanium tetra isopropoxide (TTIP), to which 0.5 mL of acetylacetone and 15 mL of 96% ethanol were added. The second solution consisted of 15 mL of 96% ethanol, 2 mL of distilled water, and 1 mL of 0.5 M acetic acid. The two solutions were then mixed and refluxed for 3 hours at 50°C while being stirred using a magnetic stirrer until the TiO_2 sol was formed. The resulting TiO_2 sol was subsequently calcined at 400°C for 1 hour to crystallize the TiO_2 nanoparticles. Finally, the nanoparticles were characterized using Scanning Electron Microscopy (SEM), X-ray diffraction (XRD), and Fourier Transform Infrared Spectroscopy (FTIR).

2.2. Characterization of synthesized TiO_2 NPs.

An X-ray diffractometer (XRD) was used to assess the phase composition, crystal structure, and crystallite size of the TiO_2 NPs at 40 keV and 40 mA. Processing of XRD results was done with the Origin Pro-8 software. The morphology and elemental composition were confirmed using field emission scanning electron microscopy energy dispersive X-ray (FESEM-EDX). Furthermore, the Fourier transform infrared (FTIR) was examined to see the functional group. Processing of FTIR results was also done with the original Pro-8 software.

2.3. Preparation of chili seedlings.

The chili seeds used in this study were high-quality seeds of the ORI 212 variety. Before sowing, the seeds were soaked in distilled water for several minutes to enhance germination rates and select seeds of poor quality. Seeds that were considered poor had a lighter weight and would experience a floating process when soaked; these seeds would be discarded and not used. At the same time, seeds that were considered to have a heavyweight would be taken and then sown on the prepared planting medium. This process lasted 14 days before the plants were transplanted into polybags filled with planting media assigned a code.

2.4. Experimental design of the field application study.

A soil fertilization test was conducted on five different polybags containing chili plant seed. At each polybag, five different soil fertilization treatments were implemented: 1) a control group with no fertilizer application; 2) the implementation of local fertilization; 3) the application of rice husk; 4) the application of TiO_2 NPs; and 5) a combined treatment involving the application of both rice husk (Treatment 3) and TiO_2 NPs (Treatment 4). Furthermore, a dose of each fertilizer formula is applied to the chili plant at 3 g, and the plants are observed in the third week after planting. After that, a test was conducted on the growth parameters of chili plants, including stem diameter, plant height, number of leaves, leaf width, and wet weight.

3. Results and Discussion

3.1. XRD analysis.

The powder X-ray diffraction (XRD) pattern of TiO₂ nanoparticles annealed at 400°C, with corresponding Miller indices (hkl), is illustrated in Figure 1. Multiple diffraction peaks were observed in the synthesized sample, all of which can be distinctly ascribed to the characteristic peaks of TiO₂, and are consistent with the anatase phase according to the JCPDS-ICDD card No. 21-1272 [25]. The prominent peaks, corresponding to the (101), (004), (200), (211), and (204) planes, suggest a well-ordered crystalline structure at 2θ values of 25.17°, 38.67°, 47.88°, and 53.87°, respectively [26,27]. Based on the Debye-Scherrer equation, the calculated crystallite size of 21 nm indicated nanoscale dimensions, which are critical for their potential applications in agriculture, particularly as a nano-fertilizer for enhancing chili plant growth.

Previous studies have demonstrated that the crystallite size of nanoparticles plays a critical role in their effectiveness as nanofertilizers. The smaller nanoparticles, with high surface-area-to-volume ratios, exhibit enhanced interactions with plant root systems, thereby improving nutrient uptake and promoting plant growth. For example, studies by Kamal *et al.* [28] have indicated that smaller crystallite sizes enhance the penetration of nano-TiO₂ particles into plant cells, facilitating the transport of nutrients such as nitrogen, phosphorus, and potassium in the cowpea plant. Moreover, Chahardoli *et al.* [29] emphasized that anatase-phase TiO₂, with nanoscale crystallite sizes, exhibits superior photocatalytic activity, thereby enhancing the plant's ability to absorb light and convert it into energy.

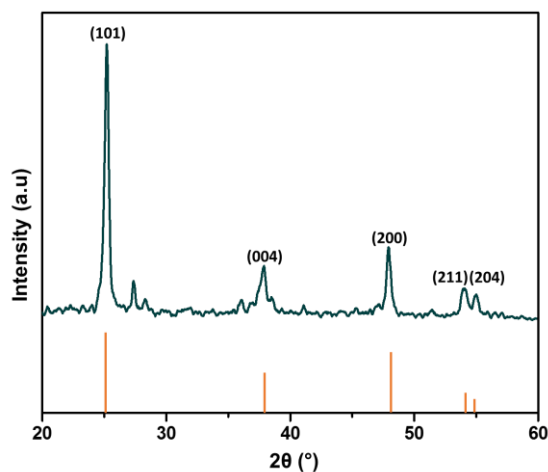


Figure 1. X-ray diffractogram of TiO₂ nanoparticles.

3.2. FTIR analysis.

The FTIR transmission spectrum of the TiO₂ nanoparticles synthesized is presented in Figure 2. To verify the presence of functional groups associated with TiO₂, the nanoparticles' chemical structure was analyzed by FTIR spectroscopy. Notable absorption bands can be observed at 3478.68 cm⁻¹, 2954.58 cm⁻¹, 2450.26 cm⁻¹, 1647.97 cm⁻¹, and 459.97 cm⁻¹, confirming the successful synthesis of TiO₂ nanoparticles (Table 1). A broad absorption peak at 3478.68 cm⁻¹ can be attributed to O-H stretching, indicating the presence of hydroxyl groups on the surface of the nanoparticles [30]. This is common in metal oxide nanoparticles, where surface hydroxylation can result from exposure to atmospheric moisture. Additionally, the peak

at 2954.58 corresponds to C-H stretching vibrations, which may be related to residual organic compounds or precursors used during synthesis. The peak at 2450.26 cm^{-1} is also associated with the bending vibrations of adsorbed water molecules (O-H bending), a feature common to nanoparticles synthesized in an aqueous environment [31].

Furthermore, the absorption band at 1747.95 cm^{-1} is characteristic of C=O stretching, suggesting the presence of carbonyl groups, possibly from organic compounds used during synthesis. The sharp absorption peaks at lower wavenumbers, specifically at 459.97 cm^{-1} , are characteristic of Ti-O-Ti stretching vibrations, confirming the formation of the TiO_2 lattice [32,33]. These peaks are consistent with the anatase phase of TiO_2 , which is known to exhibit strong absorption in this region due to its crystal structure. The prominent Ti-O bond vibrations in this region reinforce the observation that the nanoparticles synthesized exhibit the desired anatase phase, with high purity, as indicated by the absence of significant contaminant peaks in the spectrum.

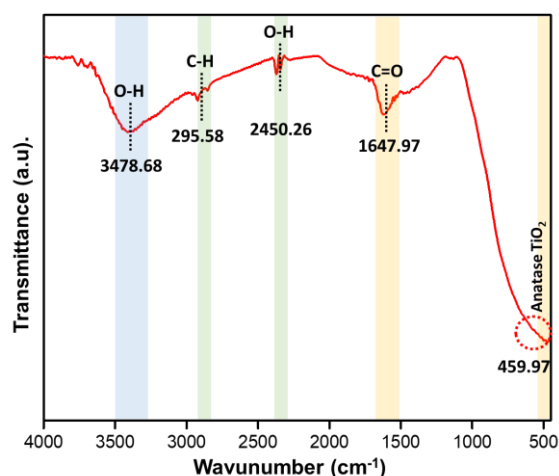


Figure 2. FTIR spectrum of anatase TiO_2 nanoparticles.

Table 1. The infrared absorption and functional group of TiO_2 nanoparticles.

Wavenumbers (cm^{-1})	Functional group
3478.68	O-H stretch
2954.58	C-H stretch
2450.26	O-H bending
1647.97	C=O
459.97	Anatase TiO_2

3.3. FESEM analysis.

Figure 3 presents the FESEM images of nanoparticle TiO_2 calcined at 400°C at different magnifications to provide detailed insights into their structural characteristics and elemental composition. At a magnification of 1000× (Figure 3a), the FESEM image reveals the overall spherical shape of the TiO_2 nanoparticles and a relatively uniform particle size distribution. The surface morphology appears smooth, with some evidence of particle agglomeration, a typical feature of nanoparticles due to their high surface energy [34]. At a high magnification of 3000 times (Figure 3b), the image provides a more detailed view of the nanoparticle surface and interparticle interactions. The surface texture becomes more discernible, and the presence of small pores or roughness can be observed, which may contribute to the material's mesoporosity. A closer inspection also reveals the aggregation behavior of the TiO_2 nanoparticles, leading to the formation of larger structures from smaller nanocrystallites.

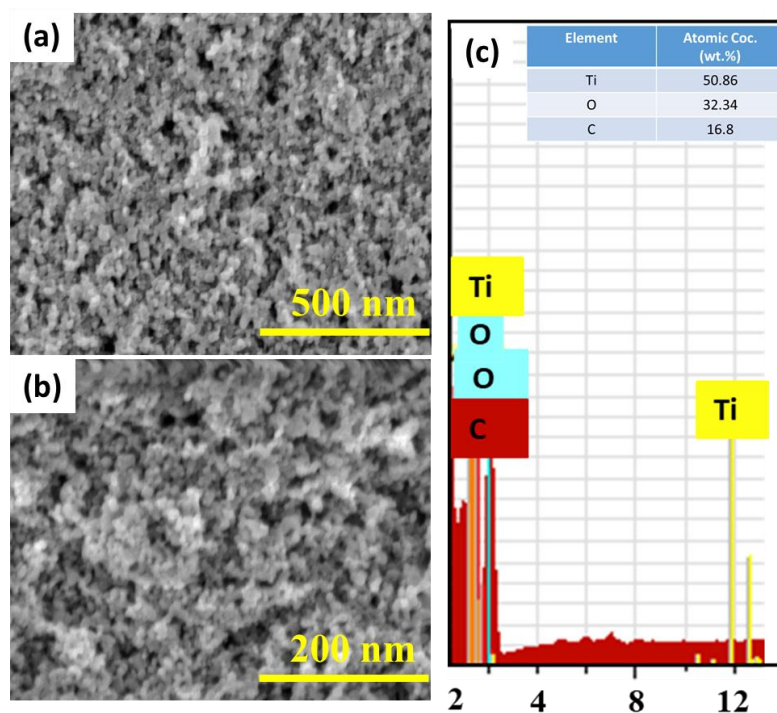


Figure 3. Morphology of nanoparticle TiO₂ analyzed by FESEM–EDX, (a) magnification of 1000 times; (b) magnification of 3000 times; (c) EDX spectra of nanoparticle TiO₂.

The EDX spectrum (Figure 3c) further confirms the elemental composition of the synthesized nanoparticles. The spectrum indicates a strong presence of titanium (Ti), oxygen (O), and carbon (C), with compositions of 50.86%, 32.34%, and 16.8%, respectively, confirming the formation of TiO₂. The absence of significant peaks for other elements suggests a high-purity product with minimal contamination.

3.4. Plant height, diameter, and number of leaves.

One of the most important indicators of vegetative development and general plant vitality is plant height. Chili plants grow more quickly in the early stages of development because of vigorous cell division and elongation; however, as the plant ages, this rate usually decreases. This is because the plant directs most of its energy into developing flowers and fruits rather than continuing to spread vegetatively. Based on the experiment (Figure 4), the control group without fertilizer treatment exhibited the slowest growth, indicating that nutrients provided by the soil alone were insufficient for optimal growth. The NPK fertilizer treatment resulted in a notable increase in plant height compared to the control, rice husk, and TiO₂ NPs, highlighting the effectiveness of a balanced nutrient supply in promoting vegetative growth.

Although rice husk has lower nutrient availability than traditional fertilizers, it has been shown to improve soil aeration and organic matter content, which may explain the moderate increase in plant height observed with this treatment. In contrast, the plants treated with TiO₂ nanoparticles (NPs) showed a significantly greater increase in height. Moreover, TiO₂ NPs' beneficial effects may be related to their capacity to boost photosynthesis, enhance light absorption, and maybe raise the efficiency of water and nutrient uptake. In contrast, the treatment combining TiO₂ NPs-rice husk showed the greatest increase in plant height. The combination of rice husk, which improved soil structure and moisture retention, and TiO₂ NPs, which enhanced nutrient absorption and growth, likely produced a synergistic effect. This

implies that by maximizing both nutrient availability and soil health, the combined application of TiO₂ NPs and rice husk waste may be an effective strategy for enhancing chili plant growth.

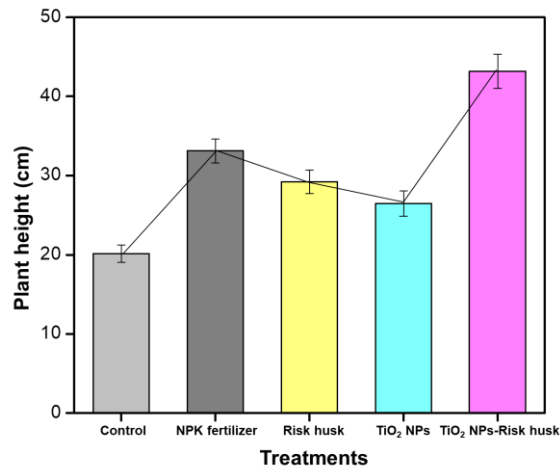


Figure 4. Plant height of chili plant with various treatments.

Stem diameter is one critical growth parameter that indicates the overall health and structural stability of plants. The capacity of chili plants to transport nutrients, water, and photosynthates, all necessary for the plant's growth and fruit production, is directly correlated with the diameter of the stem [35,36]. This study examined the impact of several treatments on the stem diameter of chili plants. Among these treatments were control (without fertilizer), NPK fertilizer, rice husk TiO₂ NPs, and a combination of TiO₂ NPs-rice husk. Figure 5, Chili plants in the control group treatment, shows the shortest stem diameters since they did not get any fertilizer. The plants' growth was restricted by the lack of additional nutrient input, as they relied solely on naturally occurring soil nutrients, which were insufficient to support healthy development. Compared with the control, rice husk, and TiO₂ NPs, plants treated with traditional NPK fertilizer had a greater stem diameter. The macronutrients nitrogen (N), phosphorus (P), and potassium (K) found in NPK fertilizer are vital for plant growth. Stem thickening is facilitated by nitrogen, which encourages vegetative growth; phosphorus, which helps root development; and potassium, which enhances water regulation and nutrient delivery.

Further, the treatment of rice husk and TiO₂ NPs slightly improved the stem diameter compared to the control. However, since rice husk has low nutrient content, its effects on stem diameter were modest, primarily improving soil physical properties rather than directly providing nutrients. TiO₂ nanoparticles have been shown to enhance photosynthesis by improving light absorption and energy conversion efficiency in plants. This, in turn, boosts overall plant growth, including stem diameter. Additionally, TiO₂ NPs may facilitate the uptake of nutrients, thereby enabling the absorption and utilization of essential elements for growth. However, it does not have a strong effect on the stem diameter. Overall, the combination of TiO₂ NPs and rice husk achieved the greatest increase in stem diameter among all treatments. This synergistic effect is likely due to the complementary roles of TiO₂ NPs and rice husk. While the TiO₂ nanoparticles enhanced photosynthesis and nutrient uptake, the rice husk improved soil structure and water retention, creating optimal conditions for plant growth. Furthermore, the organic matter in rice husk may have served as a slow-release nutrient source, sustaining plant growth over time.

The number of leaves in plants is an important indicator of overall plant health and growth, directly impacting photosynthesis efficiency and biomass production [37,38]. It's

visible (Figure 6) that the control group (without treatment) exhibited the lowest number of leaves, indicating a lack of sufficient nutrients for optimal growth.

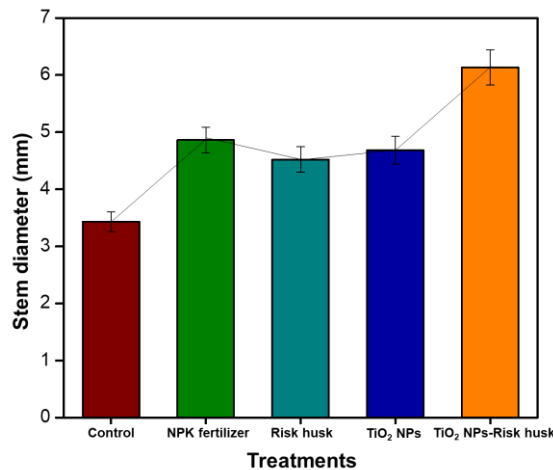


Figure 5. Stem diameter of chili plant with various treatments.

The plants treated with NPK fertilizer and rice husk showed an improvement in leaf number compared to the control and TiO₂ NPs, as NPK supplies essential macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) that promote vegetative growth. Moreover, rice husk has the ability to improve soil structure and retain moisture, thereby enhancing nutrient availability. However, the combination of TiO₂ NPs-rice husk achieved the highest number of leaves among all treatments. This synergistic effect is attributed to the dual roles of rice husk as a soil conditioner and TiO₂ nanoparticles as a nanofertilizer, which enhance nutrient absorption and plant growth. The rice husk provides a slow release of nutrients, while the TiO₂ nanoparticles facilitate more efficient uptake, ultimately resulting in the best growth performance, as reflected in the significant increase in leaf number. Table 2 compares results with recent studies that applied combined organic/inorganic nanobased fertilizers.

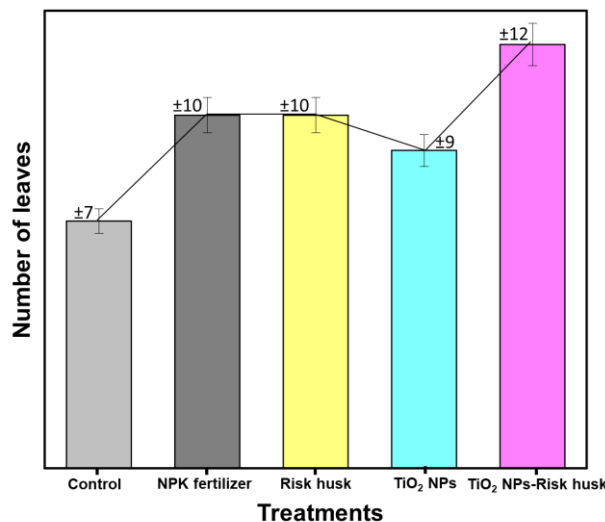


Figure 6. The number of leaves of the chili plants with various treatments.

Table 2. Comparison of recent studies using combined organic/inorganic nano-based fertilizers.

Type of fertilizer	Crop	Ref.
Bulk ZnO particles	Wheat	[39]
nano-hydroxyapatite	Camellia oleifera	[40]
Arbuscular mycorrhizal fungi-TiO ₂	Salvia officinalis L	[41]
Urea -rich sodium alginate	Tomato	[42]
Biochar-ZnO NPs	Wheat	[43]
TiO ₂ NPs-risk husk	Chili	This work

4. Conclusions

Briefly, we investigated different fertilization treatments such as Control (without fertilizer), NPK fertilizer, rice husk waste, TiO₂ NPs, and TiO₂ NPs-rice husk on growth and nutrient uptake in chili plants. The TiO₂ NPs were synthesized using the sol-gel method and calcined at 400°C. These findings indicate that TiO₂ NPs-rice husk application influenced specific growth parameters such as plant height, diameter, and number of leaves. The result also revealed that the application of TiO₂ NPs-rice husk nano fertilizer is more effective than other fertilizer treatments. Therefore, the provision of TiO₂ NPs-rice nanofertilizer is recommended for optimizing chili productivity and enhancing quality.

Author Contributions

Methodology, I. I.; Validation, I. I.; Formal analysis, Ri. R., Ro. R., and F. M.; Investigation, Ri. R., Ro. R., and F. M.; Writing – original draft, Ri. R.; Writing – review & editing, I. I.; Supervision, I. I.; Project administration, Ri. R.; Funding acquisition, Ri. R. All authors have read and agreed to the published version of the manuscript.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data supporting the findings of this study are available upon reasonable request from the corresponding author.

Funding

This research was funded by the Ministry of Education, Culture, Research and Technology of the Republic of Indonesia under the Research on Affirmation Beginner Lecturers grant no 115/E5/PG.02.00/PL/2024, 579/LL9/PK.00.PG/2024 and 03/K.P/LPPM-ITBM/VI/2024 and thank the Institut Teknologi dan Bisnis Muhammadiyah Kolaka for supporting this research.

Acknowledgments

We acknowledge the laboratory facilities' support from the Institut Teknologi dan Bisnis Muhammadiyah Kolaka.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Singh, R.P.; Handa, R.; Manchanda, G. Nanoparticles in sustainable agriculture: An emerging opportunity. *J. Control. Release* **2021**, *329*, 1234-1248, <https://doi.org/10.1016/j.jconrel.2020.10.051>.
2. Jiang, M.; Song, Y.; Kanwar, M.K.; Ahammed, G.J.; Shao, S.; Zhou, J. Phytonanotechnology applications <https://nanobioletters.com/>

- in modern agriculture. *J. Nanobiotechnol.* **2021**, *19*, 430, <https://doi.org/10.1186/s12951-021-01176-w>.
3. Ain, Q.u.; Hussain, H.A.; Zhang, Q.; Rasheed, A.; Imran, A.; Hussain, S.; Ahmad, N.; Bibi, H.; Ali, K.S. Chapter thirteen - Use of nano-fertilizers to improve the nutrient use efficiencies in plants. In Sustainable Plant Nutrition, Aftab, T., Hakeem, K.R., Eds.; Academic Press: **2023**; pp. 299-321, <https://doi.org/10.1016/B978-0-443-18675-2.00013-4>.
 4. Bhattacharya, N.; Cahill, D.M.; Yang, W.; Kochar, M. Graphene as a nano-delivery vehicle in agriculture – current knowledge and future prospects. *Crit. Rev. Biotechnol.* **2023**, *43*, 851-869, <https://doi.org/10.1080/07388551.2022.2090315>.
 5. Haydar, M.S.; Ghosh, D.; Roy, S. Slow and controlled release nanofertilizers as an efficient tool for sustainable agriculture: Recent understanding and concerns. *Plant Nano Biol.* **2024**, *7*, 100058, <https://doi.org/10.1016/j.plana.2024.100058>.
 6. Kadri, O.; Karmous, I.; Kharbech, O.; Arfaoui, H.; Chaoui, A. Cu and CuO Nanoparticles Affected the Germination and the Growth of Barley (*Hordeum vulgare* L.) Seedling. *Bull. Environ. Contam. Toxicol.* **2022**, *108*, 585-593, <https://doi.org/10.1007/s00128-021-03425-y>.
 7. Mehmood, S.; Ou, W.; Ahmed, W.; Bundschuh, J.; Rizwan, M.; Mahmood, M.; Sultan, H.; Alatalo, J.M.; Elnahal, A.S.M.; Liu, W.; Li, W. ZnO nanoparticles mediated by *Azadirachta indica* as nano fertilizer: Improvement in physiological and biochemical indices of *Zea mays* grown in Cr-contaminated soil. *Environ. Pollut.* **2023**, *339*, 122755, <https://doi.org/10.1016/j.envpol.2023.122755>.
 8. Shah, G.A.; Ahmed, J.; Iqbal, Z.; Hassan, F.-u.; Rashid, M.I. Toxicity of NiO nanoparticles to soil nutrient availability and herbage N uptake from poultry manure. *Sci. Rep.* **2021**, *11*, 11540, <https://doi.org/10.1038/s41598-021-91080-y>.
 9. Mary Isabella Sonali, J.; Kavitha, R.; Kumar, P.S.; Rajagopal, R.; Gayathri, K.V.; Ghfar, A.A.; Govindaraju, S. Application of a novel nanocomposite containing micro-nutrient solubilizing bacterial strains and CeO₂ nanocomposite as bio-fertilizer. *Chemosphere* **2022**, *286*, 131800, <https://doi.org/10.1016/j.chemosphere.2021.131800>.
 10. Zhao, C.; Xu, J.; Bi, H.; Shang, Y.; Shao, Q. A slow-release fertilizer of urea prepared via biochar-coating with nano-SiO₂-starch-polyvinyl alcohol: Formulation and release simulation. *Environ. Technol. Innov.* **2023**, *32*, 103264, <https://doi.org/10.1016/j.eti.2023.103264>.
 11. Yaushева, E.V.; Sizova, E.; Gavrish, I.A.; Lebedev, S.; Kayumov, F.G. Effect of Al₂O₃ nanoparticles on soil microbiocenosis, antioxidant status and intestinal microflora of red Californian worm (*Eisenia foetida*). *Agric. Biol.* **2017**, *52*, 191-199, <https://doi.org/10.15389/agrobiology.2017.1.191eng>.
 12. Fahad, Balouch, A.; Agheem, M.H.; Memon, S.A.; Baloch, A.R.; Tunio, A.; Abdullah; Pato, A.H.; Jagirani, M.S.; Panah, P.; Gabole, A.A.; Qasim, S. Efficient mitigation of cadmium and lead toxicity in coriander plant utilizing magnetite (Fe₃O₄) nanofertilizer as growth regulator and antimicrobial agent. *Int. J. Environ. Anal. Chem.* **2022**, *102*, 3868-3879, <https://doi.org/10.1080/03067319.2020.1776861>.
 13. Zhang, L.; Ren, Z.; Chen, H.; Huang, F.; Huang, Y.; Chu, G. Effects of nano-TiO₂/Fe₃O₄ addition on soil phosphorus fractions, microbial characteristics, and plant growth. *J. Soils Sediments* **2024**, *24*, 275-288, <https://doi.org/10.1007/s11368-023-03631-7>.
 14. Li, X.; Ghanizadeh, H.; Han, Z.; Wang, Q.; Li, F.; Qiu, Y.; Zhang, Y.; Chen, X.; Liu, J.; Wang, A. Metabolic profile and physiological mechanisms underlying the promoting effects of TiO₂NPs on the photosynthesis and growth of tomato. *Sci. Hortic.* **2023**, *322*, 112394, <https://doi.org/10.1016/j.scienta.2023.112394>.
 15. Karvar, M.; Azari, A.; Rahimi, A.; Maddah-Hosseini, S.; Ahmadi-Lahijani, M.J. Titanium dioxide nanoparticles (TiO₂-NPs) enhance drought tolerance and grain yield of sweet corn (*Zea mays* L.) under deficit irrigation regimes. *Acta Physiol. Plant.* **2021**, *44*, 14, <https://doi.org/10.1007/s11738-021-03349-4>.
 16. Kolenčík, M.; Nemček, L.; Šebesta, M.; Urík, M.; Ernst, D.; Kratošová, G.; Konvičková, Z. Effect of TiO₂ as Plant Growth-Stimulating Nanomaterial on Crop Production. In Plant Responses to Nanomaterials: Recent Interventions, and Physiological and Biochemical Responses, Singh, V.P., Singh, S., Tripathi, D.K., Prasad, S.M., Chauhan, D.K., Eds.; Springer International Publishing: Cham, **2021**; pp. 129-144, https://doi.org/10.1007/978-3-030-36740-4_5.
 17. Zahra, Z.; Waseem, N.; Zahra, R.; Lee, H.; Badshah, M.A.; Mehmood, A.; Choi, H.-K.; Arshad, M. Growth and Metabolic Responses of Rice (*Oryza sativa* L.) Cultivated in Phosphorus-Deficient Soil Amended with TiO₂ Nanoparticles. *J. Agric. Food Chem.* **2017**, *65*, 5598-5606, <https://doi.org/10.1021/acs.jafc.7b01843>.
 18. Bakshi, M.; Liné, C.; Bedolla, D.E.; Stein, R.J.; Kaegi, R.; Sarret, G.; Pradas del Real, A.E.; Castillo-Michel, H.; Abhilash, P.C.; Larue, C. Assessing the impacts of sewage sludge amendment containing nano-TiO₂ on tomato plants: A life cycle study. *J. Hazard. Mater.* **2019**, *369*, 191-198,

- <https://doi.org/10.1016/j.jhazmat.2019.02.036>.
19. Sheikhalipour, M.; Gohari, G.; Esmailpour, B.; Panahirad, S.; Milani, M.H.; Kulak, M.; Janda, T. Melatonin and TiO₂ NPs Application-Induced Changes in Growth, Photosynthesis, Antioxidant Enzymes Activities and Secondary Metabolites in Stevia (*Stevia rebaudiana* Bertoni) Under Drought Stress Conditions. *J. Plant Growth Regul.* **2023**, *42*, 2023-2040, <https://doi.org/10.1007/s00344-022-10679-1>.
 20. Singh Karam, D.; Nagabovanalli, P.; Sundara Rajoo, K.; Fauziah Ishak, C.; Abdu, A.; Rosli, Z.; Melissa Muharam, F.; Zulperi, D. An overview on the preparation of rice husk biochar, factors affecting its properties, and its agriculture application. *J. Saudi Soc. Agric. Sci.* **2022**, *21*, 149-159, <https://doi.org/10.1016/j.jssas.2021.07.005>.
 21. Mahmud-Toher, A.-S.; Govender, N.; Dorairaj, D.; Wong, M.-Y. Comparative evaluation on calcium silicate and rice husk ash amendment for silicon-based fertilization of Malaysian rice (*Oryza sativa* L.) varieties. *J. Plant Nutr.* **2022**, *45*, 1336-1347, <https://doi.org/10.1080/01904167.2021.2014878>.
 22. Sekifuji, R.; Tateda, M. Study of the feasibility of a rice husk recycling scheme in Japan to produce silica fertilizer for rice plants. *Sustain. Environ. Res.* **2019**, *29*, 11, <https://doi.org/10.1186/s42834-019-0011-x>.
 23. Oladele, S.O.; Adeyemo, A.J.; Awodun, M.A. Influence of rice husk biochar and inorganic fertilizer on soil nutrients availability and rain-fed rice yield in two contrasting soils. *Geoderma* **2019**, *336*, 1-11, <https://doi.org/10.1016/j.geoderma.2018.08.025>.
 24. Maulidiyah, M.; Watoni, A.H.; Muzakkar, M.Z.; Syawal, L.O.M.; Irwan, I.; Nurdin, M.; Umar, A.A. Fe-doped TiO₂ nanocrystals as highly efficient catalysts for heterogeneous catalytic transesterification of coconut oil. *J. Taiwan Inst. Chem. Eng.* **2024**, *164*, 105705, <https://doi.org/10.1016/j.jtice.2024.105705>.
 25. Das, P.; Sen, S.K.; Manir, M.S.; Islam, M.S.; Al Mortuza, A.; Sultana, N.; Hossain, M.L.; Ahsan, M.T.; Hasan, M.R.; Islam, A.T.M.F.; Mamun, A.N.K.; Hakim, M.A. Impact of TiO₂ Nanoparticles on Seed Germination and Growth of Nonabokra Rice, Mortality of Bean Weevil, and Antibacterial and Cytotoxic Activity. *BioNanoScience* **2024**, *14*, 102-118, <https://doi.org/10.1007/s12668-023-01273-0>.
 26. Liu, X.; Chen, J.; Yang, L.; Yun, S.; Que, M.; Zheng, H.; Zhao, Y.; Yang, T.; Liu, Z. 2D/2D g-C₃N₄/TiO₂ with exposed (001) facets Z-Scheme composites accelerating separation of interfacial charge and visible photocatalytic degradation of Rhodamine B. *J. Phys. Chem. Solids* **2022**, *160*, 110339, <https://doi.org/10.1016/j.jpcs.2021.110339>.
 27. Hu, L.; Wang, R.; Wang, M.; Wang, C.; Xu, Y.; Wang, Y.; Gao, P.; Liu, C.; Song, Y.; Ding, N.; Liu, Y.; Chen, J. The inactivation effects and mechanisms of *Karenia mikimotoi* by non-metallic elements modified TiO₂ (SNP-TiO₂) under visible light. *Sci. Total Environ.* **2022**, *820*, 153346, <https://doi.org/10.1016/j.scitotenv.2022.153346>.
 28. Kamal, R.; Mogazy, A.M. Effect of Doping on TiO₂ Nanoparticles Characteristics: Studying of Fertilizing Effect on Cowpea Plant Growth and Yield. *J. Soil Sci. Plant Nutr.* **2023**, *23*, 325-337, <https://doi.org/10.1007/s42729-021-00648-0>.
 29. Chahardoli, A.; Sharifan, H.; Karimi, N.; Kakavand, S.N. Uptake, translocation, phytotoxicity, and hormetic effects of titanium dioxide nanoparticles (TiO₂NPs) in *Nigella arvensis* L. *Sci. Total Environ.* **2022**, *806*, 151222, <https://doi.org/10.1016/j.scitotenv.2021.151222>.
 30. Liu, J.; Zhang, F.; Dou, S.; Zhu, M.; Ding, L.; Yang, Y. Adsorption of serine at the anatase TiO₂/water interface: A combined ATR-FTIR and DFT study. *Sci. Total Environ.* **2022**, *807*, 150839, <https://doi.org/10.1016/j.scitotenv.2021.150839>.
 31. Mariappan, A.; Pandi, P.; Rajeswarapalanichamy, R.; Neyvasagam, K.; Sureshkumar, S.; Gatasheh, M.K.; Hatamleh, A.A. Bandgap and visible-light-induced photocatalytic performance and dye degradation of silver doped HAp/TiO₂ nanocomposite by sol-gel method and its antimicrobial activity. *Environ. Res.* **2022**, *211*, 113079, <https://doi.org/10.1016/j.envres.2022.113079>.
 32. Amouzad, S.; Khosravi, M.; Monadi, N.; Haghghi, B.; Allakhverdiev, S.I.; Najafpour, M.M. Photo-electrochemistry of metallic titanium/mixed phase titanium oxide. *Int. J. Hydrogen Energy* **2021**, *46*, 19433-19445, <https://doi.org/10.1016/j.ijhydene.2021.03.106>.
 33. Fiorenza, R.; Di Mauro, A.; Cantarella, M.; Gulino, A.; Spitaleri, L.; Privitera, V.; Impellizzeri, G. Molecularly imprinted N-doped TiO₂ photocatalysts for the selective degradation of o-phenylphenol fungicide from water. *Mat. Sci. Semicond. Process.* **2020**, *112*, 105019, <https://doi.org/10.1016/j.mssp.2020.105019>.
 34. Zhang, X.; Zhu, Z.; Rao, R.; Chen, J.; Han, X.; Jiang, S.; Yang, Y.; Wang, Y.; Wang, L. Highly efficient visible-light-driven photocatalytic degradation of gaseous toluene by rutile-anatase TiO₂@MIL-101 composite with two heterojunctions. *J. Environ. Sci.* **2023**, *134*, 21-33,

- <https://doi.org/10.1016/j.jes.2022.03.014>.
35. Ahmadi, S.Z.; Zahedi, B.; Ghorbanpour, M.; Mumivand, H. Comparative morpho-physiological and biochemical responses of *Capsicum annuum* L. plants to multi-walled carbon nanotubes, fullerene C60 and graphene nanoplatelets exposure under water deficit stress. *BMC Plant Biol.* **2024**, *24*, 116, <https://doi.org/10.1186/s12870-024-04798-y>.
 36. Ouyang, X.; Ma, J.; Liu, Y.; Li, P.; Wei, R.; Chen, Q.; Weng, L.; Chen, Y.; Li, Y. Foliar cadmium uptake, transfer, and redistribution in Chili: A comparison of foliar and root uptake, metabolomic, and contribution. *J. Hazard. Mater.* **2023**, *453*, 131421, <https://doi.org/10.1016/j.jhazmat.2023.131421>.
 37. Bhardwaj, G.; Brar, P.S.; Chauhan, A.; Bhardwaj, M. Comparison of fruit and quality parameters of tomato and capsicum by using different amount of nano ZnO through foliar and seed application. *J. Plant Nutr.* **2024**, *47*, 3767-3776, <https://doi.org/10.1080/01904167.2024.2384572>.
 38. Sun, M.; Zhao, C.; Shang, H.; Hao, Y.; Han, L.; Qian, K.; White, J.C.; Ma, C.; Xing, B. ZnO quantum dots outperform nanoscale and bulk particles for enhancing tomato (*Solanum lycopersicum*) growth and nutritional values. *Sci. Total Environ.* **2023**, *857*, 159330, <https://doi.org/10.1016/j.scitotenv.2022.159330>.
 39. Dimkpa, C.O.; Andrews, J.; Sanabria, J.; Bindraban, P.S.; Singh, U.; Elmer, W.H.; Gardea-Torresdey, J.L.; White, J.C. Interactive effects of drought, organic fertilizer, and zinc oxide nanoscale and bulk particles on wheat performance and grain nutrient accumulation. *Sci. Total Environ.* **2020**, *722*, 137808, <https://doi.org/10.1016/j.scitotenv.2020.137808>.
 40. Lin, M.; Liu, P.; Jun, L.; Zhou, W.; Yuan, J. Phosphorus Bioavailability and Migration of Hydroxyapatite in Different Sizes as Phosphorus Fertilizer in *Camellia Oleifera* Seedlings. *HortScience* **2021**, *56*, 1112-1118, <https://doi.org/10.21273/HORTSCI16038-21>.
 41. Ostadi, A.; Javanmard, A.; Amani Machiani, M.; Sadeghpour, A.; Maggi, F.; Nouraein, M.; Morshedloo, M.R.; Hano, C.; Lorenzo, J.M. Co-Application of TiO₂ Nanoparticles and Arbuscular Mycorrhizal Fungi Improves Essential Oil Quantity and Quality of Sage (*Salvia officinalis* L.) in Drought Stress Conditions. *Plants* **2022**, *11*, 1659, <https://doi.org/10.3390/plants11131659>.
 42. El Idrissi, A.; Tayi, F.; Dardari, O.; Essamlali, Y.; Jioui, I.; Ayouch, I.; Akil, A.; Achagri, G.; Dänoun, K.; Amadine, O.; Zahouily, M. Urea-rich sodium alginate-based hydrogel fertilizer as a water reservoir and slow-release N carrier for tomato cultivation under different water-deficit levels. *Int. J. Biol. Macromol.* **2024**, *272*, 132814, <https://doi.org/10.1016/j.ijbiomac.2024.132814>.
 43. Li, M.; Zhao, X.; Cheng, Y.; Wu, M.; Dong, C.; Xiang, H.; Li, Y.; Cai, Y.; Zhang, Z.; Yu, B. Zinc oxide nanoparticles coupled biochar-based slow-release fertilizer for enhanced nutrient efficiency and sustainable agriculture. *Ind. Crops Prod.* **2025**, *232*, 121265, <https://doi.org/10.1016/j.indcrop.2025.121265>.

Publisher's Note & Disclaimer

The statements, opinions, and data presented in this publication are solely those of the individual author(s) and contributor(s) and do not necessarily reflect the views of the publisher and/or the editor(s). The publisher and/or the editor(s) disclaim any responsibility for the accuracy, completeness, or reliability of the content. Neither the publisher nor the editor(s) assume any legal liability for any errors, omissions, or consequences arising from the use of the information presented in this publication. Furthermore, the publisher and/or the editor(s) disclaim any liability for any injury, damage, or loss to persons or property that may result from the use of any ideas, methods, instructions, or products mentioned in the content. Readers are encouraged to independently verify any information before relying on it, and the publisher assumes no responsibility for any consequences arising from the use of materials contained in this publication.