Ilmu Pertanian (Agricultural Science)

http://journal.ugm.ac.id/jip

Vol. 10 No. 1 August, 2025: 123–132| DOI: doi.org/10.22146/ipas.93484

The synergistic effects of zeolite and urea fertilizer on improved nitrogen use efficiency in oil palm seedling growth

Valensi Kautsar[1,2]* and Hangger Gahara Mawandha[1]

[1]Faculty of Agriculture, Institut Pertanian Stiper (INSTIPER) – Indonesia

[2]Graduate School of Plantation Management Program, Institut Pertanian Stiper (INSTIPER) – Indonesia

Jl. Nangka II, Maguwoharjo, Depok, Sleman, Daerah Istimewa Yogyakarta, 55281

*Corresponding author: valkauts@instiperjogja.ac.id

Article Info

Received : 23rd January 2024
Revised : 15th August 2025
Accepted: 22th August 2025

Keywords:
fertilizer cost efficiency,
main nursery,
oil palm seedlings, zeolite

Abstract

Nitrogen is an essential nutrient for all plants, including oil palm, and the availability of inorganic nitrogen is crucial for supporting the development of oil palm from the seedling stage. However, the fast-release characteristic of urea often leads to its loss before it can be absorbed by plants, resulting in low fertilizer efficiency. To address this issue, one approach is to combine urea with zeolite, a natural mineral with nutrient retention properties. The purpose of this study was to determine the effectiveness of mixing urea with zeolite in oil palm seedlings. During a three-month fertilization application in the oil palm main nursery, conventional fertilization with urea was compared with urea mixed with zeolite, both inactivated and activated, at two percentages: 20% and 40%. The addition of zeolite at various percentages and various zeolite activities produced growth similar to that of urea fertilizer without zeolite. This shows that both activated and non-activated zeolites can be utilized to reduce the amount of urea dosage used in the nursery. The adoption of zeolite at various percentages and levels of activity has the potential to improve nitrogen use efficiency (NUE) in comparison to urea. The application of zeolite led to a significant increase in nitrogen use efficiency (NUE) values. Specifically, the addition of 40% zeolite resulted in considerable NUE values of 18.76% and 22.17% for inactivated and activated zeolite, respectively. In addition to its growth-promoting effects, the use of zeolite in combination with urea can also have cost-saving benefits. The addition of 20% and 40% inactivated zeolite could reduce the cost of nitrogen fertilizer by 27.4% and 36.6%, respectively, compared to 100% urea, making it a more economical option for oil palm plantations. Furthermore, the overall cost of NPK fertilization for three months with inactivated zeolite saved 7.54%-10.09%, while activated zeolite was 5.38%–5.77%.

INTRODUCTION

Plants require nitrogen as a primary macronutrient for vegetative part growth, including roots, stems, and leaves. Nitrogen is a crucial macronutrient for plants, but it is often limited in soil or lacking in the soil. Nitrogen plays a vital role in the formation of chlorophyll, which is essential for photosynthesis (Stevens, 2019; Myrold, 2021). Excessive use of urea can damage the soil and result in a waste of costs. Urea is also a fast-release fertilizer, which means its effectiveness is low, and plants cannot absorb much of it (Rütting et al., 2018; Vejan et al., 2021).

Over the past two decades, studies have progressively elucidated zeolites' unique physicochemical properties, such as high cation exchange capacity (CEC) and water retention, which enable controlled nutrient release and reduced nitrogen losses (Ferretti et al., 2017). The practical significance of this research is underscored by the global challenge of low nitrogen

How to cite: Kautsar, V., and Mawandha, H. G. (2025). The synergistic effects of zeolite and urea fertilizer on improved nitrogen use efficiency in oil palm seedling growth. *Ilmu Pertanian (Agricultural Science)*, 10(2), pp. 123–132.

ISSN 0126-4214 (print) ISSN 2527-7162 (online)

fertilizer use efficiency, often below 55%, leading to substantial nitrogen losses through volatilization and leaching, which degrade soil, water, and air quality (Bernardi et al., 2016; Medoro et al., 2022). Given that nitrogen fertilizers constitute a major input cost and environmental concern in agriculture, improving NUE via zeolite amendments offers both economic and ecological benefits (Ravali et al., 2020). To make urea more effective, it needs to be modified into a slow-release fertilizer. Slow-release fertilizers allow for more effective absorption by plants and reduce the amount of fertilizer lost due to leaching by rainwater or evaporation (Rütting, Aronsson and Delin, 2018; Vejan et al., 2021). Coating urea with different substances, such as sulfur and zinc, can reduce nitrogen losses and improve grain yield while reducing the expenses of fertilizer application. Encapsulating urea with less soluble compounds can also help avoid volatilization and leaching losses (Mustafa et al., 2022). Besides sulfur and zinc, zeolite is a mineral that can be used to modify urea fertilizer into a slow-release fertilizer. Zeolite is an alumina silicate hydrate mineral composed of tetrahedral alumina (AlO_4) and silica (SiO_4) that form a negatively charged and porous structure. Zeolites have been widely used as cation exchangers, water softeners, molecular sieves, drying agents, adsorbents, and as catalysts in various chemical reactions (Giroto et al., 2019; Lawrencia et al., 2021). Zeolite has a high cation exchange capacity (CEC), especially after activation. Activation can be done in various ways, including physically and chemically. Physically, zeolite activation is done by heating, while chemically, activation is done by adding sulfuric acid and sodium hydroxide (Estiaty, 2007; Lawrencia et al., 2021). Research by Estiaty (2007) showed that activation can increase the CEC of zeolite by 5%.

The ability of zeolites to bind ions and slowly release them is exploited in the production of slow-release fertilizers (Estiaty, 2007). Zeolite is a typical coating material used in the production of controlled-release fertilizer or slow-release fertilizer. This is due to its low cost and intrinsic cation exchange properties, which allow for excellent regulation of the rate of nutrient release (Lawrencia et al., 2021). The ammonium released by urea fertilizer after hydrolysis is bound by zeolites added with it. Binding will be more effective if the amount of zeolite mixed into urea fertilizer is increased, as the sorption complex that can capture ammonium will also increase. As long as the soil's ammonium supply remains high, ammonium absorbed by zeolites is not instantly released into the soil solution. The supply of ammonium in the zeolite cavities is released into the soil solution once the ammonium in the soil is converted to nitrate. As a result, zeolite slows the process of ammonium conversion to nitrate (Estiaty, 2007; Lateef et al., 2016; Lawrencia et al., 2021).

The purpose of this study is to investigate the effects of urea fertilizer supplemented with zeolite, both activated and inactivated at varying percentages, on plant growth and nitrogen use efficiency (NUE) fertilization costs in the main oil palm nursery for three months. Knowing this effectiveness should help oil palm producers improve fertilizer efficiency in oil palm fields.

MATERIALS AND METHODS

Experimental design

The research was conducted from July to September 2022, arranged in a completely randomized design with five different treatments, consisting of 100% urea, 80% urea + 20% inactivated zeolite, 60% urea + 40% inactivated zeolite, 80% urea + 20% activated zeolite, and 60% urea + 40% activated zeolite. Natural zeolite was used as non-activated control. A commercially activated zeolite (as supplied) was used as the activated counterpart, with no further in-house activation. The treatments were replicated six times. To effectively coat urea fertilizer, zeolite was first pulverized. The coating process was done by hand, by combining urea and zeolite at the specified percentages. A 3% (w/v) starch solution was mist-sprayed sparingly as a binder at approximately 5–10 mL per kg of urea–zeolite blend. The binder was applied uniformly and solely to improve granule cohesion, with negligible nutrient contribution. The created fertilizer was then sifted to a size of about 1-2 cm (Figure 1). Too-small granule may lead to rapid nutrient release, while too-large granule may delay release and complicate uniform application (Morrow et al., 2025).

Top layer of Entisol (0-30 cm) was sieved as planting medium in 40 x 40 cm polybags from Kali Kuning, Maguwoharjo Village, Depok, Sleman, Yogyakarta. Polybags were placed in a 6 × 6 m UV-protected greenhouse. Oil palm seedlings with uniform agronomic conditions (plant height, number

(a) (b) (c)

Figure 1. (a) Fertilizer produced by combining zeolite with urea (b) oil palm seedlings in the main nursery, and (c) measurement of oil palm seedlings

Table 1. Schedule, type, and amount of fertilization for 3 months in the main nursery

Seedling age (weeks)	Urea + zeolite	100% urea	SP-36	KCl
	g/polibag			
13	1.3	1.3	1.67	1.42
15	-	1.3	1.67	1.42
16	1.3	-	-	-
17	-	1.3	1.67	1.42
19	1.3	1.3	1.67	1.42
21	-	1.96	2.50	2.13
22	1.96	-	-	-
23	-	1.96	2.50	2.13
25	1.96	1.96	2.50	2.13
Total	7.82	11.08	14.18	12.07

of leaves, and stem diameter) were selected to be planted in the main nursery with a distance of 40 x 40 cm to provide space for the seedlings to grow well after being planted in the pre-nursery using smaller polybags measuring 20 x 15 cm for 3 months. In general, the planting distance in the main nursery of oil palm plantations is 90 cm, however, because the study period was only three months, 40 cm was chosen in this study. Watering to field capacity was done twice a day, in the morning and evening. Weeds developing in and around the polybags were removed on a regular basis during the weeding procedure. Hand picking was used to manage pests.

To assess the effect of slow-release ability, 100% urea fertilization was done twice a week, while urea fertilization mixed with zeolite was done once every 3 weeks. Fertilizers containing P and K were applied every two weeks. SP-36 was utilized as a P fertilizer, and KCl was used as a K fertilizer. Fertilization was carried out in accordance with Table 1, adjusted for the age of the oil palm seedlings.

Plant Measurement

Plant measurements observed in the main nursery included the increase in plant height, leaf number, stem diameter, and root volume over a three-month period. The difference between the last week of observation and the beginning was used to determine the increment value. Root-to-shoot ratio (RSR) was calculated with equation (1). RSR is an important parameter for plant growth as it relates to the plant's ability to absorb nutrients and grow properly. The average nitrogen content of 6-month-old oil palm seedlings was assumed to be 2.23% based on values reported by Law et al. (2012). This value of nitrogen content was used to calculate nitrogen use efficiency (NUE) according to equation (2).

$$RSR = \frac{\text{total root dry weight}}{\text{total shoot dry weight}} \quad \text{.........................(1)}$$

$$NUE = \frac{\text{total nitrogen taken up by plants}}{\text{total nitrogen applied to plants}} \times 100\% \quad \text{.....(2)}$$

The cost of fertilization was estimated using the assumption that each sack holding 50 kg of urea cost IDR 360,000, and SP-36 and KCl each cost IDR 400,000, to determine the cost efficiency resulting from the production of slow-release fertilizer using zeolite. Inactivated and activated zeolite of 25 kg cost IDR 50,000 and IDR 150,000, respectively. The starch price is IDR 15,000 per kg, and cost of labor for urea-zeolite fertilizer production was IDR 90,000 per day. All prices and labor costs were based on market values in January 2024.

Statistical Analysis

One-way ANOVA was conducted to determine differences between treatments. As a post hoc test, Tukey HSD 5% test was used. All statistical analyses were performed using SPSS version 26 (IBM Corp., Armonk, New York, USA). Correlation matrix was performed using Pearson correlation with RStudio software version 2023.09.1+494 (Posit, PBC, Boston, Massachusetts, USA).

RESULTS AND DISCUSSION

Agronomic Parameters

Plant nutrition is one of the most important variables influencing the growth of plants since it provides the chemicals that are necessary for organic synthesis. One of the essential nutrients for plants is nitrogen. Nitrogen is a primary macro-element, which is needed by plants in large quantities, but generally, the amount in the soil is very limited, so nitrogen is almost always given in the form of fertilizer. The primary causes of N deficit in crops include leaching, volatilization, surface runoff, denitrification, and plant canopy loss.

In a study conducted at the oil palm main nursery, the addition of zeolite to urea had a significant effect ($p < 0.05$) on plant height and seedling diameter. The 40% inactivated zeolite treatment produced significantly taller plants than the 100% urea treatment, while the 40% activated zeolite treatment resulted in a very significant increase ($p < 0.01$) in stem diameter compared to 100% urea (Table 2). This shows that the addition of zeolite has a very good impact on several agronomic parameters of oil palm seedlings in the main nursery during the 3-month study.

Meanwhile, leaf number increment in the 100% urea treatment was significantly higher than that in the 20% inactivated zeolite treatment. However, for the other zeolite treatments (whether activated or inactivated), leaf number increment did not differ significantly from 100% urea. Similarly, root volume was not significantly affected by the addition of zeolite at any percentage or activation status. This indicates that the addition of zeolite to urea given at 3-week intervals is able to maintain the number of leaves and root volume just like the addition of 100% urea given at 2-week intervals. Therefore, the addition of zeolite to urea can increase the growth of oil palm seedlings, but has no significant effect on the number of leaves and root volume.

Matrix Correlation

Most of the parameters studied showed a strong correlation. An increase in plant height exhibited correlation with an increase in fresh weight and root dry weight at value of 0.41 ($P < 0.05$) and 0.53 ($P < 0.01$), respectively. In addition, a very strong correlation was detected in shoot fresh weight and root fresh weight, which revealed a correlation value of 0.67 ($P < 0.001$) (Figure 2). The correlation between the shoot and root of oil palm seedlings provides information on

Table 2. Effect of zeolite-added urea application on agronomic parameters in oil palm main nurseries

Treatments	Plant height increment (cm)	Leaves number increment	Stem diameter increment (mm)	Root volume (cm^3)
100% urea (0% zeolite)	19.97 ± 5.95 b	5.25 ± 1.50 a	10.5 ± 0.5 b	25.0 ± 12.9 ab
20% inactivated zeolite	21.06 ± 1.49 ab	5.00 ± 0.63 b	15.0 ± 2.4 ab	25.0 ± 5.50 b
20% activated zeolite	24.40 ± 5.67 ab	5.33 ± 0.52 a	15.3 ± 4.8 ab	35.0 ± 13.8 ab
40% inactivated zeolite	26.32 ± 4.48 a	5.80 ± 0.45 a	13.7 ± 3.6 ab	38.0 ± 8.40 a
40% activated zeolite	25.56 ± 2.68 ab	5.83 ± 0.75 a	18.3 ± 2.5 a	26.7 ± 8.20 ab

Remarks: Values are given as mean ± standard deviation. Different letters in the same column indicate significant differences according to Tukey HSD test.

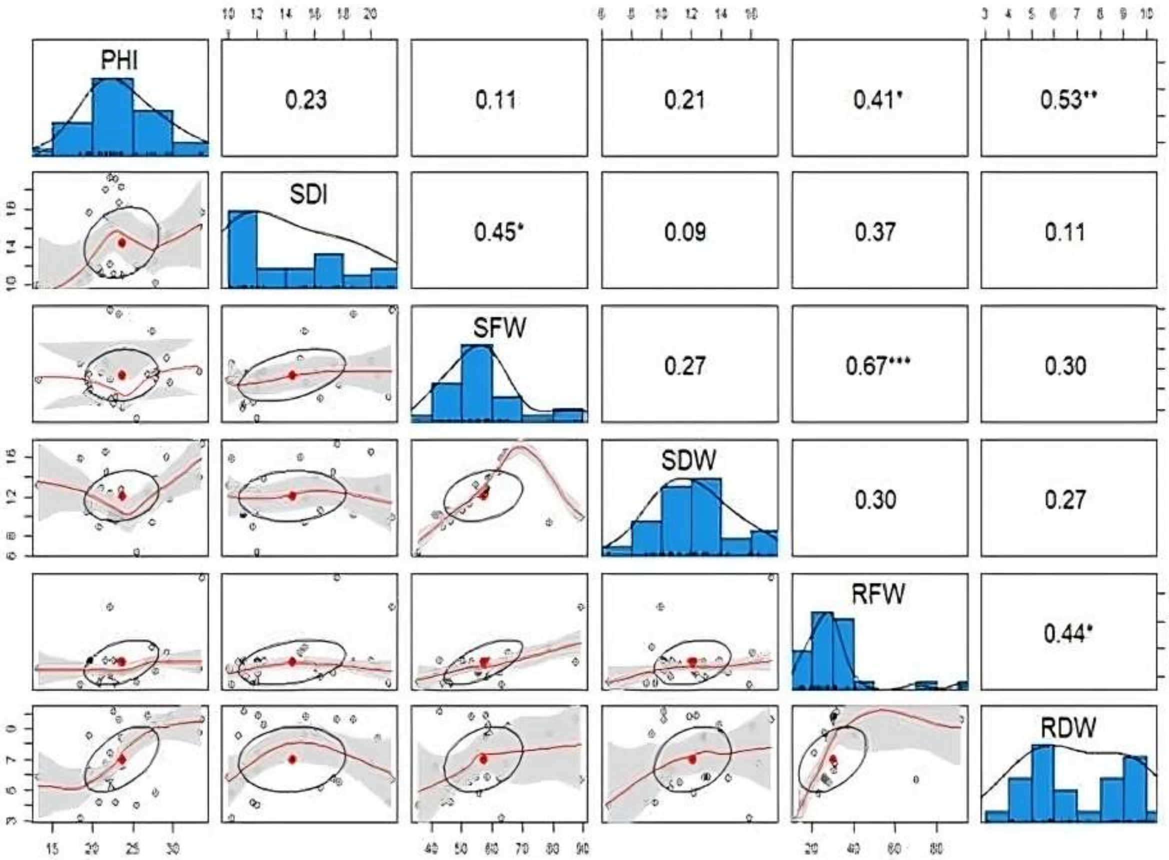

Figure 2. Pearson correlation matrix of plant parameters of oil palm seedlings in main nurseries. Numbers in columns indicate correlation coefficients. *: significant at 5% level, **: significant at 1% level, and ***: significant at 0.1% level. PHI: plant height increment, SDI: stem diameter increment, SFW: shoot fresh weight, SDW: shoot dry weight, RFW: root fresh weight, RDW: root dry weight

plant morphology, where the more roots, the higher the shoot weight. The dry weight of the shoot of oil palm seedlings is determined by the activity of plant roots in the transportation of water and nutrients moving throughout the plant body. Mineral absorption is governed by the shoot, which promotes the roots to increase mineral absorption. Minerals absorbed by the roots are then further employed by plants in the synthesis of various kinds of proteins, nucleic acids, and chlorophyll present in the leaves (Pessarakli, 2002).

RSR and NUE Value

Root-to-shoot ratio (RSR) affects plant health, output, and resilience. This method can also estimate plant and ecosystem biomass and carbon storage below ground. Understanding the root-to-shoot ratio variables helps us manage and conserve plant species. The addition of 40% activated or 40% inactivated zeolite showed higher RSR, but they were not significantly different from 100% urea (Figure 3). The RSR is a quantitative metric used to assess the distribution of biomass allocation between a plant's root system and its above-ground shoots. The measurement can serve as an indicator of the overall well-being, development, and physiological reaction of a plant. Plants exhibit varying root-to-shoot ratios, which are influenced by a combination of genetic, environmental, and physiological variables. Roots and shoots serve distinct purposes within the context of a plant's physiology. The primary functions of roots encompass the absorption of water and nutrients from the soil, providing stability to the plant through anchorage and facilitating interplant communication. Shoots play a crucial role in various physiological processes like as photosynthesis, transpiration, reproduction, and defense mechanisms. In order to optimize growth and survival, a plant must effectively allocate nutrients between its roots and shoots.

A greater root-to-shoot ratio signifies that the plant allocates a larger proportion of its resources towards root development rather than shoot development.

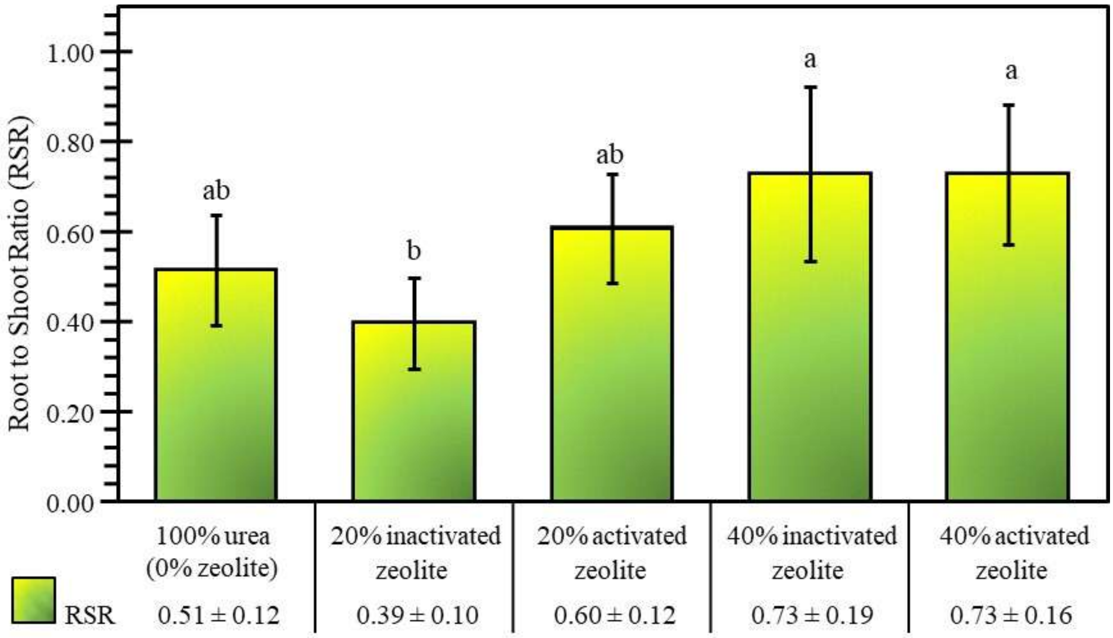

Figure 3. Root-to-shoot ratio (RSR) values in the urea treatment added with zeolite.
Values are given as mean ± standard deviation. Different letters indicate significant differences according to Tukey HSD test.

A diminished ratio of root-to-shoot signifies that the plant allocates a greater proportion of its resources towards the development and growth of its shoots, as opposed to its roots. The ratio between root and shoot biomass is subject to variation based on the plant's developmental stage, prevailing environmental circumstances and the presence of stressors. As an illustration, it is observed that juvenile plants typically exhibit diminished root-to-shoot ratios in comparison to adult plants, as a consequence of their imperative need for rapid growth and light acquisition. Plants inhabiting soils with limited nutrient availability typically exhibit elevated root-to-shoot ratios compared to plants thriving in nutrient-abundant soils since they necessitate increased exploration of soil volume to get essential nutrients. Plants experiencing drought stress have elevated root-to-shoot ratios compared to plants in optimal water circumstances, as a result of their imperative to enhance water uptake efficiency.

The primary forms of nitrogen uptake by roots are nitrate (NO_3^-) and ammonium (NH_4^+). In soils that have undergone oxidation, the major form of nitrogen is nitrate (NO_3^-), and the primary mechanism of nitrogen uptake is by absorption of this particular form. Optimal growth of the majority of annual crops can be achieved with the controlled provision of NH_4^+ and NO_3^- combinations (Kautsar et al., 2022; Maimunah et al., 2022). Concentration values are used in agriculture to assess crop plant nutrient levels. Plant tissue concentrations are more reliable markers of agricultural plant nutrition due to their stability and utility, regardless of soil, plant, and climatic circumstances. Plants can adjust nutrient intake to meet growth needs. The growing medium had significant nutrient concentration changes, but plant tissue had little change. Nutrient uptake data can indicate soil fertility depletion and crop productivity. Nutrient accumulation in crop plants matched dry matter accumulation. Nitrogen is the main component of amino acids, proteins, nucleic acids, and secondary plant compounds like alkaloids. For optimal grain production, nitrogen absorption, translocation, assimilation, and redistribution, systems must work well. (Rütting, Aronsson and Delin, 2018).

An addition of zeolite at various percentages and levels of activity indicated a notable enhancement in nitrogen use efficiency (NUE) relative to urea, with the exception of the treatment using 20% inactivated zeolite (Figure 4). The application of urea with a concentration of 100% demonstrated a nitrogen use efficiency (NUE) of merely 8.03%. This observation indicates that an enormous amount of nitrogen fertilizer is not assimilated by plants, mostly due to the composition of the planting medium being predominantly sandy. Consequently, the soil's ability to retain nutrients is compromised. The addition of 20% inactivated zeolite

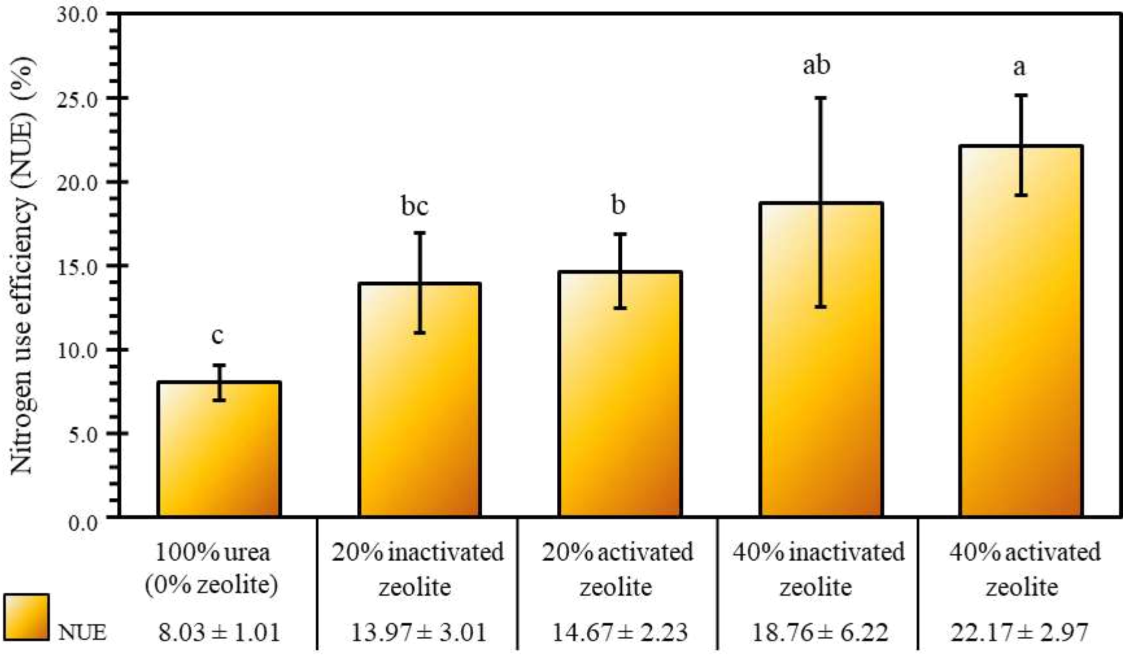

Figure 4. Nitrogen use efficiency (NUE) values in the urea treatment added with zeolite. Values are given as mean ± standard deviation. Different letters indicate significant differences according to Tukey HSD test.

resulted in a notable enhancement in nitrogen use efficiency (NUE), reaching a value of 13.97%. However, this gain was not found to be statistically significant when compared to the use of 100% urea. When using 20% inactivated zeolite, there was an observed enhancement in nitrogen use efficiency (NUE) to a value of 13.97%. However, this improvement was not found to be statistically significant when compared to the application of 100% urea. The addition of zeolite resulted in a notable improvement, as evidenced by a statistically significant rise in nitrogen use efficiency (NUE) to 14.67%, which differed from the NUE seen with 100% urea. In the present study, the incorporation of 40% zeolite resulted in notable nitrogen use efficiency (NUE) values of 18.76% and 22.17% for inactivated and activated zeolite, respectively. The concept of controlled release refers to the deliberate and regulated release of a substance over a specific period of time. The addition of zeolite in the development of slow-release urea have been identified as viable means to enhance nitrogen use efficiency (NUE) in several crop species. Research on the impact of zeolite application on nitrogen use efficiency (NUE) in mineral agricultural soils has emerged as a critical area of inquiry due to its potential to enhance fertilizer efficiency, reduce environmental pollution, and sustain crop productivity (Jakkula and Wani, 2018; Mondal et al., 2021). When applied as a soil amendment at approximately 5–7.5 t ha^{-1}, zeolite enhances the physicochemical properties of the soil, including moisture retention, porosity, and CEC. This improvement supports greater nitrogen uptake by crops, both in grain and total biomass, and boosts water use efficiency (WUE). In a multi-site maize trial conducted under Mediterranean conditions, application at 7.5 t ha^{-1} resulted in higher grain nitrogen uptake, total plant nitrogen uptake, and WUE compared with the untreated control (Kakabouki et al., 2025).

Zeolite application has been widely documented to enhance several key soil properties relevant to nutrient management and plant productivity. Consistent improvements in CEC have been reported, alongside increased retention of essential nutrients (particularly NH_4^+, K^+, and NO_3^-) and enhanced soil pH buffering capacity (GirijaVeni et al., 2021). These benefits are often accompanied by greater soil moisture retention and higher water use efficiency, which in turn promote better nutrient availability to plants (Jakkula and Wani, 2018; Aslam et al., 2021). In several cases, zeolite amendments have also been shown to increase soil organic carbon and stimulate microbial activity, thereby supporting long-term soil health and biological functioning. However, some studies have noted temporary changes in soil pH and interactions with soil organic matter that can influence nitrogen transformation processes, indicating that the effects of zeolite may vary depending on soil type, management practices, and environmental conditions (Ferretti et al., 2017).

This research includes the existing procedure in plantation companies using urea applications that are given at regular intervals to increase nitrogen fertilizer efficiency, especially in sandy soil. It is useful to apply N to sandy soils and in locations with significant rainfall. N leaching is a prevalent occurrence in this particular region, primarily attributed to the presence of sandy soils and abundant rainfall. The nitrogen use efficiency (NUE) is supposedly affected by both the rate and timing of nitrogen fertilizer application. One potential strategy to enhance the efficacy of nitrogen (N) fertilizer for crops cultivated in humid environments is the utilization of split applications of fertilizer N (Kautsar, Ismawanto and Parwati, 2022; Safitri et al., 2022). When nitrogen (N) is applied to crops at the recommended rates, it results in higher nitrogen use efficiency (NUE) and minimizes nitrogen losses. When nitrogen (N) is supplied at rates beyond the optimal level for achieving optimum economic yield, there is a buildup of nitrogen in the soil profile, resulting in elevated nitrogen losses. Conversely, if nitrogen is applied below the recommended dose, the NUE value is also not optimal, as the plants do not get enough nutrients during their growth period (Ravali et al., 2020; Medoro et al., 2022; Kakabouki et al., 2025).

Fertilizer Cost Efficiency

The cost of fertilization in oil palm plantations is substantial, accounting for approximately 30-40% of the overall maintenance expenses (Azahari and Sukarman, 2023). As a result, the implementation of the right fertilization strategy will provide significant benefits in achieving an increase in overall cost efficiency, and in in turn will have a positive impact on increasing profits for both farmers and the company. The fluctuating prices of fertilizers on a monthly basis serve as a determinant of the magnitude of profits obtained from oil palm farming endeavors. In nursery management, it is essential to use appropriate fertilization practices to ensure that plant growth does not become a hindrance in the future, considering that oil palm plants can yield for up to 25 years or even longer. Urea, SP-36, and KCl, which include nitrogen (N), phosphorus (P), and potassium (K), are the three primary nutrients that are necessary for the cultivation of oil palm, including in the major nursery stage. The cost of fertilizing the three nutrients over a period of three months amounts to IDR 2,897,760 for 10,000 seedlings (Table 3). Based on many price assumptions, including the cost of producing urea-zeolite fertilizer, the utilization of urea mixed with 20% inactivated zeolite demonstrates a lower cost of 27.4% for urea fertilization. The addition of 40% inactivated zeolite even demonstrates a better cost efficiency of 36.6% compared to urea. This indicates that the utilization of inactivated zeolite is one of the best options to achieve same growth with lower nitrogen fertilizer expenditure. Furthermore, the utilization of activated zeolite, albeit being slightly more expensive, still demonstrates cost efficiencies in fertilization of 19.6% and 21.0% compared to 100% urea. Both inactivated and activated zeolite have great potential for use in obtaining the same growth of oil palm seedlings at a lower cost. The cost of nitrogen fertilization is important as economic information if zeolite will be used for mixing with urea. This is because there is no information on the cost effectiveness of nitrogen fertilization using zeolite.

Furthermore, overall fertilization costs for N, P, and K with the addition of 20% and 40% inactivated zeolite, respectively, exhibited efficiencies of 7.54% and 10.09%. The values were higher compared to the 20% and 40% activated zeolite applications, showing cost efficiencies of 5.38% and 5.77% respectively, compared to the standard fertilization

Table 3. Cost of fertilizer used per 10,000 oil palm seedlings in the main nursery for 3 months

Treatments	Nitrogen fertilizer cost (IDR)	Nitrogen cost efficiency (%)	Phosphorus fertilizer cost (IDR)	Potassium fertilizer cost (IDR)	Total fertilizer cost (IDR)	Total fertilizer cost efficiency (%)
100% urea (0% zeolite)	797,760	–	1,134,400	965,600	2,897,760	–
20% inactivated zeolite	579,212	27.4	1,134,400	965,600	2,679,212	7.54
20% activated zeolite	641,772	19.6	1,134,400	965,600	2,741,772	5.38
40% inactivated zeolite	505,384	36.6	1,134,400	965,600	2,605,384	10.09
40% activated zeolite	630,504	21.0	1,134,400	965,600	2,730,504	5.77

conducted in the oil palm plantation for 10,000 main nursery seedlings using urea, SP-36, and KCl. In some companies, NPK fertilizer is applied in one application using NPK compound fertilizer. The utilization of compound fertilizer NPK is considered highly advantageous due to its ease of application. However, the relatively high cost per sack, ranging from IDR 730,000 to 850,000, results in an increased fertilization expense. The use of compound fertilizer NPK over a period of 3 months amounts to 40.5 g/polybag, resulting in a fertilization cost ranging from IDR 5,913,000 to 6,885,000 when applied to 10,000 seedlings.

CONCLUSIONS

This study evaluated the synergistic effects of zeolite addition to urea fertilizer on the growth performance and nitrogen use efficiency (NUE) of oil palm seedlings in the main nursery. The findings indicate that incorporating zeolite into urea fertilization can enhance overall seedling growth while maintaining leaf number and root volume comparable to 100% urea application. The addition of 40% zeolite, in both activated and inactivated forms, improved NUE significantly, with values reaching 22.17% and 18.76%, respectively. These results demonstrate that zeolite serves as an effective urea enhancer, contributing to better agronomic performance, more efficient nitrogen utilization, and potential reductions in fertilization costs for oil palm seedling production.

REFERENCES

Aslam, M.A. et al. (2021). Effects of biochar and zeolite integrated with nitrogen on soil characteristics, yield and quality of maize (*Zea mays* L.). Pakistan Journal of Botany, 53(6). Available at: https://doi.org/10.30848/PJB2021-6(27).

Azahari, D.H. and Sukarman. (2023). Impact of chemical fertilizer on soil fertility of oil palm plantations in relation to productivity and environment', IOP Conference Series: Earth and Environmental Science, 1243(1), p. 012020. Available at: https://doi.org/10.1088/1755-1315/1243/1/012020.

Bernardi, A.C.D.C. et al. (2016). Enhancing Nutrient Use Efficiency Using Zeolites Minerals—A Review. Advances in Chemical Engineering and Science, 06(04), pp. 295–204. Available at: https://doi.org/10.4236/aces.2016.64030.

Estiaty, L.M. (2007). Zeolit Alam Cikancra Tasikrnalaya Media Penyimpan Ion Amonium dari Pupuk Amonium Sulfat. Prosiding Geoteknologi LIPI [Preprint]. Available at: https://jrisetgeotam.lipi.go.id/index.php/proceedings/article/view/945 (Accessed: 29 October 2023).

Ferretti, G., Di Giuseppe, D., Natali, C. Faccini, B., Bianchini, G., and Coltortoi, M. (2017). C-N elemental and isotopic investigation in agricultural soils: Insights on the effects of zeolitite amendments. Geochemistry, 77(1), pp. 45–52. https://doi.org/10.1016/j.chemer.2017.02.002.

GirijaVeni, V., Reddy, K.S., Sharma, K.L., Shankar, K.S., and Rohhit, J. (2021). Role of Zeolites in Improving Nutrient and Water Storage Capacity of Soil and Their Impact on Overall Soil Quality and Crop Performance. in Rakshit, A., Singh, S.K., Abhilash, P.C., and Biswas, A. (eds) Soil Science: Fundamentals to Recent Advances. Singapore: Springer, pp. 449–467. https://doi.org/10.1007/978-981-16-0917-6_23.

Giroto, A.S., Guimarães, G.G., Colnago, L.A., Klamczynski, A., Glenn, G., and Ribeiro, C. (2019). Controlled release of nitrogen using urea-melamine-starch composites. Journal of Cleaner Production, 217, pp. 448–455. https://doi.org/10.1016/j.jclepro.2019.01.275.

Jakkula, V.S. and Wani, S.P. (2018). Zeolites: Potential soil amendments for improving nutrient and water use efficiency and agriculture productivity. Scientific Reviews & Chemical Communications. 8(1), pp. 1–15.

Kakabouki, I., Roussis, I., Mavroeidis, A., Stavropoulos P., Kanatas, P., Pantaleon, K., Folina, A., Beslemes, D., and Tigka, E. (2025). Effects of Zeolite Application and Inorganic Nitrogen Fertilization on Growth, Productivity, and Nitrogen and Water Use Efficiency of Maize (*Zea mays* L.) Cultivated Under Mediterranean Conditions. Sustainability, 17(5), p. 2178. https://doi.org/10.3390/su17052178.

Kautsar, V., Tang, S., Kimani, S.M., Tawaraya, K., Wu, J., Toriyama, K., Kobayashi, K., and Cheng, W. (2022). Carbon decomposition and nitrogen mineralization of foxtail and milk vetch incorporated into paddy soils for different durations of organic farming. Soil Science and Plant Nutrition, 68(1), pp. 158–166. https://doi.org/10.1080/00380768.2021.2024424.

Kautsar, V., Ismawanto, D., and Parwati, W.D.U. (2022). The response of oil palm seedlings' growth to vermicompost and water stress under the main nursery stage. Jurnal Pertanian Tropik, 9(3, Dec), pp. 232–239. https://doi.org/10.32734/jpt.v9i3.

Lateef, A., Nazir, R., Jamil, N., Alam, S., Shah, R., Khan, M.N, and Saleem, M. (2016). Synthesis and characterization of zeolite based nano–composite: An environment friendly slow release fertilizer. Microporous and Mesoporous Materials, 232, pp. 174–183. https://doi.org/10.1016/j.micromeso.2016.06.020.

Law, C.C., Zaharah, A.R., Husni, M.H.A., and Akmar, A.S.N. (2012). Evaluation of Nitrogen Uptake Efficiency of Different Oil Palm Genotypes Using 15N Isotope Labelling Method. Pertanika Journal of Tropical Agricultural Science. 35(4), pp. 755–766.

Lawrencia, D. Wong, S.K., Low, D.Y.S., Goh, B.H., Goh, J.K., Ruktanonchai, U.R., Soottitantawat, A., Lee, L.H., and Tang S.Y. (2021). Controlled Release Fertilizers: A Review on Coating Materials and Mechanism of Release. Plants, 10(2), p. 238. https://doi.org/10.3390/plants10020238.

Maimunah, M.A., Kautsar, V., Bimantara, P.U., Kimani, S.M., Utami, A.I., Sabri, R.K., Tawaraya, K., Utami, S.N.H., Purwanto, B.H., and Cheng, W. (2022). Weeding Frequencies Improve Soil Available Nitrogen in Organic Paddy Field. Planta Tropika: Jurnal Agrosains (Journal of Agro Science), 10(1), pp. 45–54. https://doi.org/10.18196/pt.v10i1.12707.

Medoro, V., Ferreti, G., Galamini, G., Rotondi, A., Morrone, L., Faccini, B., and Coltorti, M. (2022). Reducing Nitrogen Fertilization in Olive Growing by the Use of Natural Chabazite-Zeolitite as Soil Improver', Land, 11(9), p. 1471. https://doi.org/10.3390/land11091471.

Mondal, M., Biswas , B., Garai, S., Sarkar, S., Banerjee, H., Brahmachari, K., Bandyopadhyay, P.K., Maitra, S., Brestic, M., Skalicky, M., Ondrisik, P., and Hossain A. (2021). Zeolites Enhance Soil Health, Crop Productivity and Environmental Safety. Agronomy, 11(3), p. 448. https://doi.org/10.3390/agronomy11030448.

Mustafa, A., Athar, F., Khan, I., Chattha, M.U., Nawaz, M., Shah, A.N., Mahmood, A., Batool, M., Aslam, M.T., Jaremko, M., Abdelsalam, N.R., Ghareeb, R.Y., and Hassan, M.U. (2022). Improving crop productivity and nitrogen use efficiency using sulfur and zinc-coated urea: A review. Frontiers in Plant Science, 13. https://www.frontiersin.org/articles/10.3389/fpls.2022.942384.

Myrold, D.D. (2021). 15 - Transformations of nitrogen. in T.J. Gentry, J.J. Fuhrmann, and D.A. Zuberer (eds) Principles and Applications of Soil Microbiology (Third Edition). Elsevier, pp. 385–421. https://doi.org/10.1016/B978-0-12-820202-9.00015-0.

Pessarakli, M. (ed.) (2002). Handbook of plant and crop physiology. 2nd ed., rev.expanded. New York: M. Dekker (Books in soils, plants and the environment, v. 84).

Ravali, C.H., Rao, K.J., Anjaiah, T., and Suresh, K. (2020). Influence of Zeolite on Nitrogen Fractions, Nitrogen Use Efficiency and Nitrogen Uptake of Maize. International Research Journal of Pure and Applied Chemistry. pp. 297–307. https://doi.org/10.9734/irjpac/2020/v21i2330327.

Rütting, T., Aronsson, H., and Delin, S. (2018). Efficient use of nitrogen in agriculture. Nutrient Cycling in Agroecosystems, 110(1), pp. 1–5. https://doi.org/10.1007/s10705-017-9900-8.

Safitri, L., Hermantoro, Kautsar, V., Suparyanto, T., Hidayat, A.A., and Pardamean, B. (2022). Sustainability of the Water Footprint of Various Soil Types on Oil Palm Plantations. IOP Conference Series: Earth and Environmental Science, 998(1), p. 012004. https://doi.org/10.1088/1755-1315/998/1/012004.

Stevens, C.J. (2019). Nitrogen in the environment. Science, 363(6427), pp. 578–580. https://doi.org/10.1126/science.aav8215.

Vejan, P., Khadiran, T. Abdullah, R., and Ahmad, N. (2021). Controlled release fertilizer: A review on developments, applications and potential in agriculture. Journal of Controlled Release, 339, pp. 321–334. https://doi.org/10.1016/j.jconrel.2021.10.003.