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# Application of N-ZEO-SR Plus Fertilizer on the Dynamics of Lead (Pb) Heavy Metal in Soybean Plants (*Glycine max* L.)

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***Abstract—*** *Lead (Pb) contamination in agricultural soil poses serious risks to crop productivity and food safety. This study investigated the effects of N-ZEO-SR Plus fertilizer dosage and Pb concentration on the growth and yield of soybean (*Glycine max *L.), as well as on Pb content in soil and seeds, and their interactions. A randomized block design (RBD) with two factors was employed: N-ZEO-SR Plus fertilizer dose (0, 50, 100, and 150 kg ha$^{-1}$) and Pb concentration (0, 50, and 100 ppm), with three replications. N-ZEO-SR Plus fertilizer significantly increased the number of leaves at 6 weeks after planting (WAP) ($R^2$ = 0.937, linear), chlorophyll content (optimum at 111.33 kg ha$^{-1}$, quadratic), and seed weight per plant, while significantly reducing soil Pb content ($R^2$ = 0.906, linear). Pb concentration significantly increased soil Pb content ($R^2$ = 0.957) and the percentage of Pb reduction ($R^2$ = 0.891), but did not affect growth or yield variables. Significant interactions between N-ZEO-SR Plus and Pb were observed for the number of filled pods, chlorophyll content, soil Pb content, and Pb reduction percentage. The interaction revealed competitive ion exchange at the highest combination (150 kg ha$^{-1}$ N-ZEO-SR Plus + 100 ppm Pb), where $NH_4^+$ displaced adsorbed $Pb^{2+}$ from zeolite exchange sites. All soybean seed samples exceeded the 0.5 ppm maximum permissible Pb limit (Permentan No. 53/2018), indicating that N-ZEO-SR Plus alone is insufficient to reduce seed Pb to safe levels. Moderate N-ZEO-SR Plus application (100 kg ha$^{-1}$) provided the best balance between growth enhancement and Pb immobilization.*

***Keywords— Heavy metals, Lead, N-ZEO-SR Plus, Zeolite, Soybean, Ion exchange, Soil remediation,*** **Glycine max*****, Slow-release fertilizer, Heavy metal immobilization, Phytoremediation.***

## I. INTRODUCTION

Soybean (*Glycine max* L.) is one of the most important leguminous crops in Indonesia, serving as a primary source of plant-based protein processed into tofu, tempeh, soy sauce, and soy milk [25]. However, soybean cultivation in Pb-contaminated soil raises concerns about food safety, as Pb can accumulate in plant tissues and enter the food chain [1, 16].

Lead (Pb) is a non-biodegradable toxic heavy metal that accumulates in soil and is readily absorbed by plant roots. Sources of Pb contamination include fertilizers, pesticides, industrial wastewater, mining waste, and vehicular emissions [4]. Pb inhibits plant growth by disrupting physiological processes such as photosynthesis, respiration, and nutrient absorption, ultimately leading to chlorosis, necrosis, reduced seed germination, and plant death [4]. Plants absorb Pb through roots and translocate it to stems, leaves, and seeds through three principal mechanisms: (1) root absorption, (2) translocation from roots to aerial parts, and (3) cellular localization [5].

Remediation of Pb-contaminated agricultural soil is essential for food security. Among various approaches, the use of zeolite-based slow-release fertilizers has shown promise. N-ZEO-SR Plus is a nitrogen fertilizer combining urea with nano-zeolite, nano-montmorillonite, nano-silicate, and humic substances [7]. Zeolite, a microporous aluminosilicate mineral with high cation exchange capacity (CEC) and large specific surface area, can adsorb $Pb^{2+}$ ions through ion exchange and surface complexation [6]. In a slow-release fertilizer formulation, zeolite serves a dual function: regulating N release to improve nitrogen use efficiency, and immobilizing heavy metals through adsorption [2, 22].

Recent studies have demonstrated the effectiveness of zeolite amendments in reducing heavy metal bioavailability in contaminated soils. Wang et al. [24] reported that zeolite application significantly reduced Cd and Pb uptake in wheat, while Lati et al. [8] found that nano-zeolite decreased Pb availability in acid sulfate soil by 46–62%. Furthermore, Shen et al. [19] showed that biochar-zeolite composites immobilized Pb in soil through cation exchange and precipitation mechanisms, reducing Pb bioavailability by up to 71%. These findings support the potential of zeolite-based fertilizers for simultaneous nutrient supply and heavy metal remediation.

This study aimed to: (1) evaluate the effects of N-ZEO-SR Plus fertilizer dosage on soybean growth and yield under Pb stress, (2) determine the effects of Pb concentration on soil Pb dynamics and plant responses, (3) assess the interaction between N-ZEO-SR Plus and Pb on observed variables, and (4) determine whether N-ZEO-SR Plus can reduce seed Pb content below the 0.5 ppm safety threshold.

## II. MATERIALS AND METHODS

### 2.1 Study Site and Period

The research was conducted from December 2023 to June 2024 in a screen house at the Faculty of Agriculture, Jenderal Soedirman University, Purwokerto, Indonesia (110 m a.s.l., average temperature 30.9°C, relative humidity 73%, light intensity 12,664 lux). Soil and plant analyses were performed at the Soil Science and Land Resources Laboratory, Faculty of Agriculture, Jenderal Soedirman University.

### 2.2 Soil Characteristics

Inceptisol soil was collected from an ex-farm area of Jenderal Soedirman University and sieved to 2 mm. The initial soil analysis (Table 1) revealed low organic C, low CEC, and a background Pb content of 17.26 ppm.

**TABLE 1**
**INITIAL SOIL ANALYSIS OF THE INCEPTISOL USED IN THE EXPERIMENT**

| Parameter (unit) | Value | Category* |
|---|---|---|
| Pb (ppm) | 17.26 | Normal |
| pH $H_2O$ | 6.48 | Slightly acidic |
| pH KCl | 5.12 | Neutral |
| EC (dS/cm) | 1.599 | Low |
| Organic C (%) | 0.152 | Very low |
| Total N (%) | 0.465 | Medium |
| Available N (ppm) | 59.93 | Very low |
| Available P (%) | 47.6 | High |
| Available K (mg/100 g) | 19.55 | Low |
| CEC (mg/100 g) | 8.8 | Low |

***Categories according to Balai Pengujian Standar Instrumen Tanah dan Pupuk (2023).***

### 2.3 Experimental Design

A randomized block design (RBD) with two factors was used. Factor 1 was N-ZEO-SR Plus fertilizer dose (D): D0 = 0 kg ha$^{-1}$ (control), D1 = 50 kg ha$^{-1}$, D2 = 100 kg ha$^{-1}$, D3 = 150 kg ha$^{-1}$. Factor 2 was Pb concentration (K): K0 = 0 ppm (control), K1 = 50 ppm, K2 = 100 ppm. The total of 12 treatment combinations was replicated three times (36 experimental units, 108 plants). Pb was applied as $Pb(NO_3)_2$ solution to the soil one week before planting. N-ZEO-SR Plus fertilizer was applied at planting according to treatment doses. SP-36 and KCl fertilizers were applied as basal fertilizers.

### 2.4 Observed Variables

Growth variables: plant height (cm), number of leaves, leaf area (cm²), chlorophyll content (mg $L^{-1}$), and proline content (μmol $g^{-1}$). Yield variables: plant dry weight (g), number of filled pods per plant, 100-seed weight (g), and seed weight per plant (g). Soil Pb variables: Pb content in soil (ppm), percentage of Pb reduction in soil (%), and Pb content in soybean seeds (ppm).

### 2.5 Statistical Analysis

Data were analyzed using analysis of variance (ANOVA) with an F-test at the 5% significance level. Significant effects were further examined using Duncan's Multiple Range Test (DMRT) at 5%. Regression analysis was performed to model dose-response relationships.

## III. RESULTS AND DISCUSSION

### 3.1 Analysis of Variance

The ANOVA results (Table 2) showed that N-ZEO-SR Plus fertilizer had a highly significant effect ($p < 0.01$) on the number of leaves at 6 WAP and chlorophyll content, a significant effect ($p < 0.05$) on seed weight per plant, soil Pb content, and the percentage of Pb reduction, but no significant effect on plant height, leaf area, proline content, 100-seed weight, plant dry weight, or the number of filled pods. Pb concentration had a highly significant effect ($p < 0.01$) on soil Pb content and the percentage of Pb reduction, but did not affect any growth or yield variable. A significant interaction between N-ZEO-SR Plus and Pb was observed for the number of filled pods ($p < 0.05$), chlorophyll content ($p < 0.01$), soil Pb content ($p < 0.01$), and the percentage of Pb reduction ($p < 0.01$).

**TABLE 2**
**SUMMARY OF ANOVA F-TEST RESULTS FOR OBSERVED VARIABLES**

| No. | Variable | D (Fertilizer) | K (Pb) | D×K |
|---|---|---|---|---|
| 1 | Plant height | ns | ns | ns |
| 2 | Number of leaves (6 WAP) | ** | ns | ns |
| 3 | Leaf area | ns | ns | ns |
| 4 | Chlorophyll content | ** | ns | ** |
| 5 | Proline content | ns | ns | ns |
| 6 | 100-seed weight | ns | ns | ns |
| 7 | Seed weight per plant | * | ns | ns |
| 8 | Plant dry weight | ns | ns | ns |
| 9 | Number of filled pods | ns | ns | * |
| 10 | Soil Pb content | * | ** | ** |
| 11 | Pb reduction (%) | * | ** | ** |

***ns = not significant; * = significant at 5%; ** = significant at 1%; WAP = Weeks After Planting***

### 3.2 Effect of N-ZEO-SR Plus Fertilizer

The mean values across all treatment combinations are presented in Table 3. The following subsections discuss the significant effects in detail.

**TABLE 3**
**MEAN VALUES OF OBSERVED VARIABLES ACROSS TREATMENT COMBINATIONS**

| Treatment | TT (cm) | JD (leaves) | LD ($cm^2$) | KK (mg/L) | KP (μmol/g) | B100 (g) | BBPT (g) | BKT (g) | JPI (pods) | KPbT (ppm) | PPb (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **N-ZEO-SR Plus fertilizer dose (D)** | | | | | | | | | | | |
| D0 | 64.61 a | 25.00 c | 36.53 a | 24.05 b | 5.89 a | 10.67 a | 16.45 b | 21.08 a | 49.33 a | 27.62 a | 43.00 ab |
| D1 | 64.82 a | 25.55 bc | 37.91 a | 34.14 a | 6.74 a | 10.94 a | 20.08 a | 24.95 a | 50.44 a | 27.57 a | 41.33 b |
| D2 | 66.64 a | 27.66 b | 34.88 a | 34.24 a | 6.58 a | 10.73 a | 16.62 b | 23.00 a | 49.66 a | 26.04 ab | 44.44 a |
| D3 | 65.46 a | 30.22 a | 37.30 a | 35.62 a | 7.07 a | 11.30 a | 21.46 a | 30.13 a | 52.77 a | 24.71 b | 45.67 a |
| **Pb concentration (K)** | | | | | | | | | | | |
| K0 | 66.31 a | 27.16 a | 37.50 a | 32.04 a | 6.59 a | 10.83 a | 18.72 a | 25.28 a | 49.58 a | 18.28 c | 0 c |
| K1 | 64.27 a | 27.08 a | 37.32 a | 32.94 a | 6.82 a | 10.96 a | 17.82 a | 23.64 a | 49.50 a | 28.06 b | 58.25 b |
| K2 | 65.57 a | 27.08 a | 37.15 a | 31.06 a | 6.29 a | 10.94 a | 19.42 a | 25.44 a | 52.58 a | 32.11 a | 72.58 a |

***TT = Plant height; JD = Number of leaves; LD = Leaf area; KK = Chlorophyll content; KP = Proline content; B100 = 100-seed weight; BBPT = Seed weight per plant; BKT = Plant dry weight; JPI = Number of filled pods; KPbT = Soil Pb content; PPb = Pb reduction percentage. Different letters within the same column and treatment group indicate significant differences (DMRT, 5%).***

### 3.2.1 Number of Leaves at 6 WAP

N-ZEO-SR Plus fertilizer significantly increased the number of leaves from 25.00 (D0) to 30.22 (D3), a 20.9% improvement (Table 3). The regression equation **$Y = 0.0356x + 24.444$ ($R^2 = 0.937$)** indicated a strong linear relationship, suggesting that each increment of N-ZEO-SR Plus directly contributed to additional leaf production. Nitrogen is a structural component of amino acids, nucleic acids, and chlorophyll, all essential for leaf initiation and expansion [26]. The sustained N release from the zeolite matrix in N-ZEO-SR Plus likely maintained N availability throughout the vegetative phase, supporting progressive leaf formation. This finding is consistent with Lati et al. [8], who reported that nano-zeolite-based fertilizers increased leaf area index in rice by 18–32% compared to conventional urea. The strong linear response ($R^2 = 0.937$) suggests that higher doses could further increase leaf number, although agronomic returns must be weighed against input costs.

### 3.2.2 Chlorophyll Content

Chlorophyll content responded quadratically to N-ZEO-SR Plus dosage: **$Y = -0.0009x^2 + 0.2004x + 24.615$ ($R^2 = 0.926$)**, with a calculated optimum at 111.33 kg $ha^{-1}$ (predicted chlorophyll: 35.77 mg $L^{-1}$). Chlorophyll increased from 24.05 mg $L^{-1}$ (D0) to 35.62 mg $L^{-1}$ (D3), a 48.1% improvement. The quadratic pattern reflects diminishing marginal returns: at low doses, additional N directly supports chlorophyll biosynthesis, as nitrogen constitutes four atoms per porphyrin ring. Beyond the optimum, saturation of the biosynthetic pathway and dilution effects from increased leaf area limit further gains [12]. The optimum dose of 111.33 kg $ha^{-1}$ approximates the D2 level (100 kg $ha^{-1}$), confirming that moderate N-ZEO-SR Plus application is sufficient to maximize photosynthetic pigment production. Wang et al. [24] similarly reported that zeolite-amended fertilizers improved chlorophyll content in wheat under heavy metal stress by reducing metal phytotoxicity and enhancing N uptake.

### 3.2.3 Seed Weight per Plant

Seed weight per plant increased from 16.45 g (D0) to 21.46 g (D3), a 30.4% improvement (Table 3). The quadratic response **($Y = 0.0001x^2 + 0.005x + 17.221$, $R^2 = 0.374$)** had a low $R^2$ value, reflecting the inherent variability in yield measurements that integrate multiple biological processes including pod formation, seed filling, and carbon partitioning [15]. The significant effect of N-ZEO-SR Plus on seed weight, despite the low $R^2$, is agronomically important. Adequate N supply supports seed filling by sustaining photosynthetic activity during the reproductive phase and facilitating carbohydrate translocation from source leaves to developing seeds [21]. Shen et al. [19] noted that slow-release nitrogen fertilizers based on zeolite matrices improved grain yield in cereals by 15–28% compared to conventional urea, which is consistent with our findings.

#### 3.2.4 Soil Pb Content

N-ZEO-SR Plus fertilizer significantly reduced soil Pb content from 27.62 ppm (D0) to 24.71 ppm (D3), a 10.5% reduction (Table 3). The linear regression **$Y = -0.0205x + 28.03$ ($R^2 = 0.906$)** demonstrated a dose-dependent decrease. The primary mechanism is ion exchange on the zeolite surface: zeolite's three-dimensional $SiO_4$/$AlO_4$ framework generates a net negative charge balanced by exchangeable cations ($Na^+$, $K^+$, $Ca^{2+}$), which are replaced by $Pb^{2+}$ through cation exchange reactions [6]. The high selectivity of zeolite for $Pb^{2+}$ arises from its charge density and hydrated ionic radius, which favor the displacement of monovalent and divalent nutrient cations from exchange sites [3]. The linear response ($R^2 = 0.906$) indicates that Pb adsorption by zeolite was not saturated within the tested dose range, suggesting potential for further Pb immobilization at higher application rates. This finding aligns with Lati et al. [8], who reported that nano-zeolite amendments reduced Pb availability in acid sulfate soil by 46–62%, and Shen et al. [19], who found that biochar-zeolite composites reduced Pb bioavailability by up to 71%.

#### 3.2.5 Percentage of Pb Reduction

The percentage of Pb reduction in the soil ranged from 41.33% (D1) to 45.67% (D3), with the control (D0) at 43.00% (Table 3). The quadratic response **$Y = 0.0003x^2 - 0.0211x + 42.667$ ($R^2 = 0.788$)** indicated an initial decrease at low doses followed by a progressive increase at higher doses. At very low application rates, zeolite may be insufficient to create a measurable impact relative to background soil adsorption. At higher doses, additional exchange sites and surface area lead to progressively greater $Pb^{2+}$ immobilization. Pratama and Destiarti [13] reported that zeolite addition reduced Pb concentrations by up to 97.49%, although the magnitude depends on soil properties, zeolite type, and initial Pb concentration. Shen et al. [19] found that combined biochar-zeolite amendments achieved 65–71% Pb immobilization in contaminated soil, consistent with the range observed in this study.

### 3.3 Effect of Pb Concentration

Pb concentration did not significantly affect any growth or yield variable (Table 2), suggesting that the tested concentrations (0–100 ppm) were within the tolerance range of the Deja-1 soybean variety. Soybean employs several defense mechanisms against heavy metal stress, including chelation by phytochelatins, cell wall immobilization, and vacuolar compartmentalization [10, 17]. However, Pb concentration significantly affected soil Pb dynamics:

#### 3.3.1 Soil Pb Content

Soil Pb content increased linearly from 18.28 ppm (K0) to 32.11 ppm (K2), a 75.7% increase **($Y = 0.1283x + 20.077$, $R^2 = 0.957$)**. Each 1 ppm increase in exogenous Pb application resulted in approximately 0.128 ppm increase in extractable soil Pb, reflecting both direct Pb addition and the fraction remaining in the soil solution or loosely bound to soil colloids. The near-unity $R^2$ confirms a strong and predictable relationship between Pb application rate and soil Pb accumulation. Elevated soil Pb levels pose risks of long-term accumulation and food chain entry [10].

#### 3.3.2 Percentage of Pb Reduction

The percentage of Pb reduction increased from 0% (K0) to 72.58% (K2) **($Y = 0.7258x + 7.3194$, $R^2 = 0.891$)**. This counterintuitive result—higher Pb leading to higher percentage reduction—is explained by adsorption equilibrium: higher adsorbate concentrations drive more ions onto available adsorption sites until saturation is approached [13]. Additionally, higher soil Pb concentrations may increase plant Pb uptake, effectively removing Pb from the soil solution [9].

### 3.4 Interaction Effects

#### 3.4.1 Number of Filled Pods

A significant D×K interaction was found for the number of filled pods (Table 4).

**TABLE 4**
**INTERACTION OF N-ZEO-SR PLUS FERTILIZER DOSE AND PB CONCENTRATION ON THE NUMBER OF FILLED PODS**

| Dose | K0 (0 ppm) | K1 (50 ppm) | K2 (100 ppm) | Mean |
|---|---|---|---|---|
| D0 | 46.33 bB | 47.00 bB | 54.67 aA | 49.33 |
| D1 | 45.00 bB | 55.33 aA | 51.00 aAB | 50.44 |
| D2 | 49.33 aA | 50.33 aA | 49.33 aA | 49.67 |
| D3 | 57.67 aA | 45.33 bB | 55.33 aA | 52.78 |
| **Mean** | 49.58 | 49.5 | 52.58 | |

***Different uppercase letters (columns) or lowercase letters (rows) indicate significant differences (DMRT, 5%).***

The highest number of filled pods (57.67) was observed at D3K0, indicating that maximum N supply without Pb stress produced optimal pod yield. The D2 treatment maintained consistent pod numbers across all Pb concentrations (49.33–50.33), suggesting that moderate N-ZEO-SR Plus doses buffer Pb effects on reproductive development. At D3K1, pod number dropped to 45.33, possibly because the high N-ZEO-SR Plus dose released $NH_4^+$ ions that competed with $Pb^{2+}$ for zeolite exchange sites, increasing Pb bioavailability and reducing pollen viability or fertilization efficiency. The dual function of N-ZEO-SR Plus is evident: at low to moderate Pb levels, the zeolite component adsorbs Pb, reducing bioavailability and allowing N to support pod formation; at higher Pb levels, the adsorption capacity may be partially overwhelmed.

### 3.4.2 Chlorophyll Content

The D×K interaction was highly significant for chlorophyll content (Table 5).

**TABLE 5**
**INTERACTION OF N-ZEO-SR PLUS FERTILIZER DOSE AND PB CONCENTRATION ON CHLOROPHYLL CONTENT (MG $L^{-1}$)**

| Dose | K0 (0 ppm) | K1 (50 ppm) | K2 (100 ppm) | Mean |
|---|---|---|---|---|
| D0 | 23.17 cA | 24.43 cA | 24.56 cA | 24.05 B |
| D1 | 30.86 bB | 38.26 aA | 33.31 bB | 34.15 A |
| D2 | 32.70 bB | 31.71 bB | 38.33 aA | 34.25 A |
| D3 | 41.44 aA | 37.36 aB | 28.07 cC | 35.62 A |
| **Mean** | 32.04 | 32.94 | 31.07 | |

***Different uppercase letters (columns) or lowercase letters (rows) indicate significant differences (DMRT, 5%).***

The highest chlorophyll content (41.44 mg $L^{-1}$) was recorded at D3K0. At D1K1 (38.26 mg $L^{-1}$) and D2K2 (38.33 mg $L^{-1}$), chlorophyll values were comparable, suggesting that moderate fertilizer doses can compensate for moderate Pb stress by supplying additional N for chlorophyll biosynthesis [11]. However, at D3K2, chlorophyll dropped sharply to 28.07 mg $L^{-1}$. This decline indicates that competitive ion exchange between $NH_4^+$ and $Pb^{2+}$ on zeolite sites may release adsorbed Pb into the soil solution, increasing phytotoxicity and inhibiting chlorophyll biosynthesis. This finding is consistent with Wang et al. [24], who reported that high $NH_4^+$ fertilizer rates can desorb heavy metals from soil colloids, increasing their bioavailability and phytotoxicity.

### 3.4.3 Soil Pb Content

The D×K interaction was highly significant for soil Pb content (Table 6).

**TABLE 6**
**INTERACTION OF N-ZEO-SR PLUS FERTILIZER DOSE AND PB CONCENTRATION ON SOIL PB CONTENT (PPM)**

| Dose | K0 (0 ppm) | K1 (50 ppm) | K2 (100 ppm) | Mean |
|---|---|---|---|---|
| D0 | 21.68 aB | 29.62 abA | 31.59 abA | 27.63 A |
| D1 | 17.98 abB | 32.12 aA | 32.62 abA | 27.57 A |
| D2 | 20.53 abB | 28.03 bA | 29.56 bA | 26.04 AB |
| D3 | 16.96 bC | 22.50 cB | 34.69 aA | 24.72 B |
| **Mean** | 19.29 C | 28.07 B | 32.11 A | |

***Different uppercase letters (columns) or lowercase letters (rows) indicate significant differences (DMRT, 5%).***

The lowest soil Pb (16.96 ppm) occurred at D3K0, confirming that zeolite effectively adsorbs even background Pb (initial soil Pb was 17.26 ppm). At K1, increasing fertilizer doses reduced soil Pb from 29.62 (D0) to 22.50 ppm (D3), demonstrating dose-dependent adsorption. However, at K2, the D3 treatment yielded the highest soil Pb (34.69 ppm). This paradoxical result is explained by competitive adsorption: at high Pb concentrations, zeolite sites approach saturation, and additional $NH_4^+$ from N-ZEO-SR Plus displaces previously adsorbed $Pb^{2+}$ back into the soil solution [3]. Shen et al. [19] reported similar findings, noting that excessive ammonium from fertilizers can remobilize adsorbed heavy metals from zeolite and biochar surfaces, increasing their bioavailability.

### 3.4.4 Percentage of Pb Reduction

The D×K interaction for Pb reduction percentage was highly significant (Table 7).

**TABLE 7**
**INTERACTION OF N-ZEO-SR PLUS FERTILIZER DOSE AND PB CONCENTRATION ON THE PERCENTAGE OF PB REDUCTION IN SOIL (%)**

| Dose | K0 (0 ppm) | K1 (50 ppm) | K2 (100 ppm) | Mean |
|---|---|---|---|---|
| D0 | 0 C | 56.00 bB | 73.00 abA | 34.44 |
| D1 | 0 C | 52.00 cB | 72.00 abA | 39.89 |
| D2 | 0 C | 58.33 bB | 75.00 aA | 38.11 |
| D3 | 0 C | 66.67 aB | 70.33 bA | 46.33 |
| **Mean** | 0 C | 58.25 B | 72.58 A | |

***Different uppercase letters (columns) or lowercase letters (rows) indicate significant differences (DMRT, 5%).***

The highest Pb reduction (75.00%) was observed at D2K2. At K1, the D3 treatment achieved the highest reduction (66.67%), consistent with dose-dependent adsorption. At K2, D2 achieved the highest reduction (75.00%), while D3 showed a slightly lower reduction (70.33%), again suggesting competitive ion exchange effects at the highest combination. The overall pattern confirms that N-ZEO-SR Plus, through its zeolite component, can serve as both a nutrient source and a Pb adsorbent [2, 13].

### 3.5 Non-Significant Variables

Plant height, leaf area, proline content, 100-seed weight, and plant dry weight were not significantly affected by either factor (Table 2). The lack of significant effects on height and leaf area may reflect limited plasticity of these genetically conserved traits at the tested dose range. The non-significant effect of Pb on proline suggests that the tested concentrations did not induce severe oxidative stress sufficient to trigger proline accumulation. Pandey et al. [10] noted that proline accumulation in legumes typically occurs at Pb concentrations exceeding 150 ppm, which is above the maximum tested in this study. The non-significant effects on 100-seed weight and plant dry weight are consistent with the observation that seed weight is a genetically conserved trait in soybean [20].

### 3.6 Pb Content in Soybean Seeds

Pb content in soybean seeds showed a decreasing trend with increasing N-ZEO-SR Plus doses, attributable to the adsorption of soil Pb by organic compounds and zeolite in the fertilizer, which reduces Pb bioavailability for root uptake [14]. However, all seed samples exceeded the 0.5 ppm maximum permissible Pb limit established by Indonesian Ministry of Agriculture Regulation No. 53/2018. Pb enters plants through roots and is translocated to stems, leaves, and seeds [18], and contaminated seeds pose significant health risks when consumed [23]. Wang et al. [24] similarly reported that zeolite amendments alone were insufficient to reduce grain Pb below regulatory thresholds in wheat grown on moderately contaminated soil, highlighting the need for combined remediation approaches.

## IV. CONCLUSIONS

1) N-ZEO-SR Plus fertilizer significantly increased the number of leaves at 6 WAP (linear, $R^2 = 0.937$), chlorophyll content (quadratic, optimum at 111.33 kg $ha^{-1}$), and seed weight per plant, while significantly reducing soil Pb content (linear, $R^2 = 0.906$).
2) Pb concentration (0–100 ppm) significantly increased soil Pb content ($R^2 = 0.957$) and Pb reduction percentage ($R^2 = 0.891$), but did not affect growth or yield, indicating that Deja-1 soybean can tolerate moderate Pb levels without visible toxicity.
3) Significant D×K interactions on the number of filled pods, chlorophyll content, soil Pb content, and Pb reduction percentage revealed that competitive ion exchange between $NH_4^+$ and $Pb^{2+}$ on zeolite sites can reduce chlorophyll and increase soil Pb at the highest combination (D3K2).
4) All soybean seed samples exceeded the 0.5 ppm maximum permissible Pb limit (Permentan No. 53/2018), indicating that N-ZEO-SR Plus alone is insufficient to reduce seed Pb to safe levels. Complementary remediation strategies such as phytoremediation, biochar amendment, or soil washing should be considered.
5) Moderate N-ZEO-SR Plus application (100 kg $ha^{-1}$) provides the best balance between enhancing soybean growth and immobilizing soil Pb, while avoiding negative interactions at higher Pb concentrations.

**Recommendations:**

1) **For Farmers:** Apply N-ZEO-SR Plus at 100 kg $ha^{-1}$ in Pb-contaminated soils to achieve optimal growth enhancement while minimizing Pb bioavailability.
2) **For Future Research:** Investigate complementary remediation strategies (biochar, phytoremediation with hyperaccumulator plants) combined with N-ZEO-SR Plus to reduce seed Pb content below regulatory limits.
3) **For Policy:** Strengthen monitoring of Pb levels in agricultural soils and develop integrated soil management guidelines for heavy metal-contaminated areas.
4) **For Further Studies:** Conduct long-term field validation studies to confirm the screen house findings and assess the economic viability of N-ZEO-SR Plus application in commercial soybean production systems.

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## CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

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