

Dose-Dependent Interaction Between Moringa Leaf Extract and NPK Fertilization on Vegetative Growth and Reproductive Biomass of Common Bean (*Phaseolus vulgaris* L.)

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ABSTRACT

Integration of bio stimulants with mineral fertilization has gained increasing attention as a sustainable strategy to enhance crop productivity. *Moringa leaf extract* (MLE) is recognized for its bioactive compounds that may improve plant growth and yield however, its effectiveness largely depends on nutrient availability. This study aimed to evaluate the interaction between MLE concentration and NPK fertilizer rate on the growth and production of common bean, particularly pod weight per plant. The experiment was arranged in a factorial design with four MLE concentrations (0, 5, 7.5, and 15%) and three NPK rates (350, 450, and 550 kg ha⁻¹). Data were analyzed using analysis of variance followed by the Honestly Significant Difference (HSD) test at 5%. The results revealed a significant interaction between MLE concentration and NPK rate on pod weight per plant. The highest pod weight (324.48 g per plant) was obtained with the combination of 15% MLE and 450 kg ha⁻¹ NPK. Increasing the NPK rate to 550 kg ha⁻¹ did not further enhance yield and, in some treatments, reduced the positive effect of MLE. Application is most effective when integrated with balanced mineral fertilization. The combination of 7.5-15% MLE and 450 kg ha⁻¹ NPK is recommended to optimize reproductive biomass in common bean. These findings contribute to the development of more efficient and sustainable fertilization strategies in agriculture.

INTRODUCTION

Common bean (*Phaseolus vulgaris* L.) is one of the most economically and nutritionally important legume crops cultivated worldwide, particularly in tropical and subtropical regions where it serves as a major source of dietary protein and essential micronutrients for smallholder farmers and food-insecure populations. Despite its agronomic importance, common bean productivity in many developing regions remains constrained by declining soil fertility, inefficient nutrient management, and the growing need to sustain yields under environmentally responsible agricultural practices (Belal et al., 2025).

Conventional mineral fertilization, especially NPK fertilizer, has long been the cornerstone of nutrient management in legume production systems due to its role in supporting vegetative growth, flowering, and pod formation (Zerbo et al., 2024). However, prolonged reliance on inorganic fertilizers alone has raised serious concerns related to soil degradation, low nutrient use efficiency, nutrient leaching, and environmental pollution, including greenhouse gas emissions (Mehdawe et al., 2023). These limitations highlight the urgent need for complementary, environmentally friendly strategies that can improve crop performance while reducing dependence on high chemical fertilizer inputs.

In recent years, plant-based biostimulants have emerged as promising tools to enhance crop growth, physiological performance, and yield in a more sustainable manner (Maksoud et al., 2023). Among these, *Moringa oleifera* leaf extract (MLE) has gained increasing attention due to its rich content of bioactive compounds, including cytokinins (notably zeatin), vitamins, amino acids, antioxidants, and essential macro- and micronutrients (Abotlasha et al., 2025; Khalu et al., 2025). Numerous studies have demonstrated that MLE

application can improve vegetative growth, photosynthetic activity, antioxidant defense, and yield in various horticultural and field crops (Al-Taisan et al., 2022). These effects are attributed to the stimulation of physiological and biochemical processes such as cell division, chlorophyll synthesis, nutrient uptake efficiency, and stress tolerance.

The integration of MLE with mineral fertilization is considered a promising approach to achieve synergistic effects on crop performance. Biostimulant properties of MLE may complement NPK fertilization by enhancing root development, improving nutrient use efficiency, and strengthening plant resilience to abiotic stresses, thereby potentially allowing reductions in mineral fertilizer rates without compromising yield (Khan et al., 2023; Ho et al., 2025). Such integrated nutrient management strategies are particularly relevant in tropical agroecosystems, where soil fertility constraints and climate-related stresses frequently limit legume productivity.

Although evidence of the agronomic benefits of moringa leaf extract has been widely reported for various commodities, empirical studies on the combined application of moringa leaf extract and NPK fertilizer on green beans are still relatively limited, particularly under field conditions in tropical regions (Belal et al., 2025). Furthermore, the optimal dose combination of moringa leaf extract and NPK fertilizer to maximize growth response and yield of green beans has not been systematically established. This highlights the importance of developing sustainable nutrient management strategies in legume cultivation systems.

Therefore, this study aimed to evaluate the effects of the combined application of *Moringa oleifera* leaf extract and NPK fertilizer on the growth and yield of common bean. Specifically, this research assessed key growth parameters and yield components under different treatment combinations to determine whether the integration of plant-based biostimulants with mineral fertilization could enhance crop performance in a more sustainable and environmentally sound manner. The findings are expected to contribute to the development of integrated nutrient management strategies that support both productivity and sustainability in legume production systems.

MATERIALS AND METHODS

The study was conducted at Kebun Timbak, Tobalau Hamlet, Enrekang District, Enrekang Regency, South Sulawesi, from April to July 2025. The site was selected as it represents an active vegetable cultivation area with agroecological conditions typical of highland farming systems. The planting material used was common bean seeds (*Phaseolus vulgaris* L.) cv. Maxipora F1. Other materials included soil, *Moringa oleifera* leaf extract, and NPK Mutiara fertilizer (16:16:16). The equipment used comprised hoes, machetes, watering cans, hoses, measuring tapes, a camera, a chopper/blender, cloth sieves, stationery, stakes, and trellises.

The experiment was arranged in a factorial randomized complete block design (RCBD) with two factors. The first factor was the concentration of *Moringa oleifera* leaf extract (K) with four levels: K0 (0% extract, water only), K1 (5% extract), K2 (7.5% extract), and K3 (15% extract). The second factor was the rate of NPK Mutiara fertilizer (N) with three levels: N1 (350 kg ha⁻¹, equivalent to 4.2 g plant⁻¹), N2 (450 kg ha⁻¹, equivalent to 6.0 g plant⁻¹), and N3 (550 kg ha⁻¹, equivalent to 7.2 g plant⁻¹). Each treatment combination was replicated three times, resulting in 36 experimental units. Each plot measured 1.0 m × 1.2 m with a planting spacing of 30 cm × 40 cm, resulting in nine plants per plot.

Data were analyzed using analysis of variance (ANOVA) according to the factorial RCBD. When significant effects of treatments or their interactions were detected, mean comparisons were performed using the Least Significant Difference (LSD) test at the 5% significance level. All statistical analyses were conducted at a 5% probability level.

RESULTS AND DISCUSSION

1. Plant Height

Table 1 presents the mean plant height of common bean in response to the combined application of different concentrations of *Moringa oleifera* leaf extract and NPK fertilizer rates. The data illustrate the effects of each treatment and their interaction on vegetative growth performance.

Table 1. Mean plant height (cm) as affected by different concentrations of *Moringa oleifera* leaf extract and NPK fertilizer rates on the growth and yield of common bean.

| Moringa oleifera Leaf Extract Concentration (%) | NPK Fertilizer Rate (kg ha ⁻¹) | | | LSD 5% |
|-------------------------------------------------|--------------------------------------------|----------------------------------|----------------------------------|--------|
| | NPK 350 (N1) | NPK 450 (N2) | NPK 550 (N3) | |
| 0 (K0) | 141.07 ^a _x | 140.66 ^a _y | 142.15 ^a _x | 6.50 |
| 5 (K1) | 141.03 ^a _x | 141.69 ^a _y | 143.63 ^a _x | |
| 7.5 (K2) | 142.23 ^a _x | 142.91 ^a _y | 144.32 ^a _x | |
| 15 (K3) | 143.97 ^b _x | 154.48 ^a _x | 144.57 ^b _x | |

Note: Values followed by different letters within the same row (a, b, c) and column (x, y) are significantly different according to the Least Significant Difference (LSD) test at the 5% level.

The results presented in Table 1 indicate that the concentration of *Moringa oleifera* leaf extract (MLE), NPK fertilizer rate, and their interaction significantly affected the mean plant height of common bean. The significant interaction confirms that the growth response was not determined solely by MLE application or mineral fertilization independently, but rather by their combined application. This finding is consistent with reports that plant-based biostimulants such as MLE enhance vegetative growth more effectively when integrated with balanced mineral nutrition (Masih, 2019).

The progressive increase in plant height with increasing MLE concentration, particularly the highest response observed at 15%, reinforces the role of MLE as a natural biostimulant. *Moringa* leaf extract is known to contain cytokinins (especially zeatin), auxin-like compounds, antioxidants, amino acids, vitamins, and essential macro and micronutrients that collectively stimulate cell division, chlorophyll synthesis, and enhanced metabolic activity (Layuk et al., 2022; Singh et al., 2023).

These bioactive constituents directly contribute to improved vegetative growth, particularly during early growth stages when nutrient demand and physiological activity are high. Furthermore, MLE has been reported to enhance nutrient uptake efficiency and improve plant physiological performance, thereby positively affecting plant height, leaf area, and biomass accumulation across various species (Yaseen & Hájos, 2021).

In the context of the present study, the increased plant height observed at higher MLE concentrations may be attributed to cytokinin-mediated stimulation of meristematic activity and enhanced nitrogen assimilation. This mechanism explains why the 15% MLE treatment produced the highest vegetative response when NPK availability was adequate.

The significant interaction between MLE and NPK fertilizer rate indicates that the effectiveness of MLE strongly depends on sufficient nutrient availability. Although MLE provides hormonal and antioxidant stimulation, optimal mineral nutrition is still required to sustain the increased metabolic activity of the plant. Similar interaction patterns have been reported in factorial studies involving legumes and vegetables, where combined applications of biostimulants and mineral fertilizers resulted in greater vegetative responses compared to single treatments (Soliman et al., 2024).

In this study, the combination of 15% MLE and 450 kg ha⁻¹ NPK produced the highest plant height (154.48 cm), significantly exceeding other extract concentrations at the same fertilizer level. This finding is consistent with reports indicating that moderate-to-high fertilizer rates often optimize the effectiveness of plant biostimulants (Christophe et al., 2019). Adequate nitrogen, phosphorus, and potassium availability likely facilitated more efficient utilization of growth regulators present in MLE, thereby strengthening vegetative growth.

Interestingly, increasing the fertilizer rate to 550 kg ha⁻¹ did not result in a proportional increase in plant height. The smaller numerical gain at this level suggests the occurrence of diminishing returns at excessive nutrient inputs. Similar patterns have been reported in previous studies, where excessive mineral fertilization did not enhance, and in some cases reduced, the efficiency of biostimulant treatments (Abdelkhalik et al., 2024).

This condition may be associated with nutrient imbalance, potential osmotic stress, or reduced nutrient use efficiency under excessive fertilizer inputs. Therefore, the growth response to the combination of MLE and NPK appears to follow an optimum response curve rather than a strictly linear relationship.

This interpretation is further supported by comparisons within the same MLE concentration, where plant height increased with rising NPK rates up to an optimum at 450 kg ha⁻¹, particularly at 15% MLE. Similar

findings have been reported, emphasizing that optimal mineral nutrition is required to maximize the benefits of biostimulants, whereas insufficient or excessive fertilizer rates may limit plant response (Soliman et al., 2024; Christophe et al., 2019).

These findings highlight the importance of balanced fertilization strategies in common bean cultivation. Biostimulant application alone cannot fully compensate for nutrient deficiencies, and excessive fertilization may restrict the synergistic effects between biostimulants and mineral nutrients.

The combination of 15% MLE and 450 kg ha⁻¹ NPK appears to represent the most physiologically balanced condition, in which hormonal stimulation and nutrient availability are harmonized to support maximum vegetative growth. These results strengthen the concept that integrating biostimulants with mineral fertilization is an effective approach to improving plant growth efficiency in a sustainable manner.

2. Number of Leaves

The results in Table 3 indicate that the concentration of *Moringa oleifera* leaf extract (MLE), NPK fertilizer rates, and their interaction had a significant effect on the average number of leaves of common bean plants.

Table 2. Mean number of leaves (per plant) as affected by *Moringa oleifera* leaf extract concentration and NPK fertilizer rates on the growth and yield of common bean plants.

| Moringa oleifera Leaf Extract Concentration (%) | NPK Fertilizer Rate (kg ha ⁻¹) | | | LSD 5% |
|-------------------------------------------------|--------------------------------------------|----------------------------------|---------------------------------|--------|
| | NPK 350 (N1) | NPK 450 (N2) | NPK 550 (N3) | |
| 0 (K0) | 19.33 ^a _x | 18.07 ^a _y | 18.78 ^a _x | 1.69 |
| 5 (K1) | 18.74 ^a _x | 19.56 ^a _{xy} | 19.11 ^a _x | |
| 7.5 (K2) | 20.04 ^a _x | 19.48 ^a _{xy} | 18.96 ^a _x | |
| 15 (K3) | 19.11 ^a _x | 20.56 ^a _x | 19.59 ^a _x | |

Note: Values followed by different letters within the same row (a, b, c) and column (x, y, z) are significantly different according to the 5% Honestly Significant Difference (HSD) test.

The results presented in Table 2 indicate that within the tested factorial combinations of *Moringa oleifera* leaf extract (MLE) concentrations (0–15%) and NPK fertilizer rates (350–550 kg ha⁻¹), the mean number of leaves per common bean plant was not significantly affected either by the individual factors or by their interaction at the 5% significance level. This suggests that the observed numerical differences did not exceed the statistical threshold. These findings are consistent with several studies on legumes and leafy vegetables, where the response of leaf number to biostimulants such as MLE is strongly influenced by plant species, growth stage, and nutrient conditions (Adewusi, 2024).

Although the differences shown in Table 2 were not statistically significant, a noteworthy numerical trend was observed. The highest leaf number (20.56 leaves per plant) was recorded at 15% MLE combined with 450 kg ha⁻¹ NPK, whereas the lowest value (18.07 leaves) occurred in the treatment without MLE at the same NPK rate. This pattern may indicate a slight tendency for higher MLE concentrations to support leaf formation under moderate mineral nutrition. Such an effect could be related to the presence of bioactive compounds in MLE, including cytokinins, amino acids, and micronutrients, which are known to promote cell division and enhance vegetative vigor.

Comparison among NPK rates within each MLE level in Table 2 revealed no significant differences, indicating that increasing fertilizer from 350 to 550 kg ha⁻¹ did not proportionally increase leaf number under the conditions of this study. Similarly, increasing MLE concentration did not significantly influence leaf formation across fertilizer levels. Although some studies have reported synergistic effects between biostimulants and inorganic fertilizers, such responses are generally crop- and environment-specific (Windari et al., 2021). The present findings do not provide strong evidence of such synergy for the leaf number parameter in common bean.

Based on the data summarized in Table 2, the tested MLE and NPK combinations did not consistently enhance leaf initiation or final leaf number per plant. While a slight numerical increase was observed at 15% MLE combined with a moderate NPK rate, further studies involving wider dosage ranges, different application timings, or varying environmental conditions are required to draw more robust conclusions.

3. Stem Diameter (mm)

Table 3 presents the mean stem diameter (mm) of common bean plants as affected by different concentrations of *Moringa oleifera* leaf extract and NPK fertilizer rates. The data illustrate the interaction between MLE concentrations (0–15%) and NPK application levels (350–550 kg ha⁻¹) on stem growth, with statistical differences evaluated using the 5% HSD test.

Table 3. Mean stem diameter (mm) as affected by *Moringa oleifera* leaf extract concentrations and NPK fertilizer rates on the growth and yield of common bean plants.

| Moringa oleifera Leaf Extract Concentration (%) | NPK Fertilizer Rate (kg ha ⁻¹) | | | LSD 5% |
|-------------------------------------------------|--------------------------------------------|---------------------------------|--------------------------------|--------|
| | NPK 350 (N1) | NPK 450 (N2) | NPK 550 (N3) | |
| 0 (K0) | 5.80 ^a _x | 5.97 ^a _y | 5.87 ^a _x | 0.47 |
| 5 (K1) | 6.20 ^a _x | 5.80 ^a _y | 5.93 ^a _x | |
| 7.5 (K2) | 6.37 ^a _x | 6.23 ^a _{xy} | 6.17 ^a _x | |
| 15 (K3) | 6.30 ^b _x | 6.60 ^a _x | 6.23 ^b _x | |

Note: Values followed by different letters within rows (a, b and c) and columns (x, y and z) indicate significant differences according to the 5% HSD test.

The results presented in Table 3 indicate that within the tested factorial combinations of *Moringa oleifera* leaf extract (MLE) concentrations (0-15%) and NPK fertilizer rates (350-550 kg ha⁻¹), the mean number of leaves per common bean plant was not significantly affected either by the individual factors or by their interaction at the 5% significance level. This suggests that the observed numerical differences did not exceed the statistical threshold. These findings are consistent with several studies on legumes and leafy vegetables, where the response of leaf number to biostimulants such as MLE is strongly influenced by plant species, growth stage, and nutrient conditions (Sheikha et al., 2022).

Although the differences shown in Table 3 were not statistically significant, a noteworthy numerical trend was observed. The highest leaf number (20.56 leaves per plant) was recorded at 15% MLE combined with 450 kg ha⁻¹ NPK, whereas the lowest value (18.07 leaves) occurred in the treatment without MLE at the same NPK rate. This pattern may indicate a slight tendency for higher MLE concentrations to support leaf formation under moderate mineral nutrition. Such an effect could be related to the presence of bioactive compounds in MLE, including cytokinins, amino acids, and micronutrients, which are known to promote cell division and enhance vegetative vigor.

Comparison among NPK rates within each MLE level in Table 3 revealed no significant differences, indicating that increasing fertilizer from 350 to 550 kg ha⁻¹ did not proportionally increase leaf number under the conditions of this study. Similarly, increasing MLE concentration did not significantly influence leaf formation across fertilizer levels. Although some studies have reported synergistic effects between biostimulants and inorganic fertilizers, such responses are generally crop- and environment-specific (Windari et al., 2021). The present findings do not provide strong evidence of such synergy for the leaf number parameter in common bean.

Based on the data summarized in Table 3, the tested MLE and NPK combinations did not consistently enhance leaf initiation or final leaf number per plant. While a slight numerical increase was observed at 15% MLE combined with a moderate NPK rate, further studies involving wider dosage ranges, different application timings, or varying environmental conditions are required to draw more robust conclusions.

4. Flowering Time

Table 4 presents the mean flowering time (days after sowing, DAS) of common bean plants as influenced by different concentrations of *Moringa oleifera* leaf extract and NPK fertilizer rates. The table summarizes both the main and interaction effects of MLE concentrations and NPK levels on the onset of flowering, with statistical differences determined using the 5% HSD test.

Table 4. Mean flowering age (DAS) of moringa leaf extract concentration and NPK fertilizer treatments on the growth and yield of common bean plants.

| Moringa oleifera Leaf Extract Concentration (%) | NPK Fertilizer Rate (kg ha ⁻¹) | | | Mean | LSD 5% |
|-------------------------------------------------|--------------------------------------------|--------------------|--------------------|--------------------|--------|
| | NPK 350 (N1) | NPK 450 (N2) | NPK 550 (N3) | | |
| 0 (K0) | 39.85 | 39.56 | 39.70 | 39.70 ^c | 0.47 |
| 5 (K1) | 39.26 | 39.48 | 39.26 | 39.33 ^b | |
| 7.5 (K2) | 39.19 | 38.59 | 39.33 | 39.04 ^a | |
| 15 (K3) | 38.89 | 38.74 | 39.41 | 39.01 ^a | |
| Mean | 39.30 ^b | 39.09 ^a | 39.43 ^c | | |
| LSD 5% | 0.11 | | | | |

Note: Numbers followed by different letters (a, b and c) indicate significant differences based on the 5% HSD test.

Table 4 shows that flowering time in common bean ranged from 38.59 to 39.85 DAS, with both MLE concentration and NPK fertilizer rate significantly affecting this parameter at the 5% level, although the absolute differences were relatively small. The control treatment (0% MLE) resulted in the longest time to flowering (39.70 DAS), while increasing MLE concentration tended to shorten the period to flowering, with 7.5% and 15% MLE producing the earliest flowering times (39.04 and 39.01 DAS, respectively). This trend is consistent with previous reports that biostimulants such as MLE can accelerate phenological development by influencing plant growth regulators, amino acids, and micronutrient availability involved in floral initiation (Lagiotis et al., 2023). However, the magnitude of this change was relatively small and highly dependent on genotype and environmental conditions.

The tendency toward earlier flowering at higher MLE concentrations may be associated with cytokinin- or auxin-like compounds present in MLE, which regulate hormonal balance and plant developmental timing. In addition, amino acids and micronutrients supplied through MLE application may enhance plant vigor and accelerate the transition to the reproductive phase when supported by adequate soil fertility. Nevertheless, as widely reported in the literature, the effects of biostimulants on phenology are strongly context-dependent and do not always produce uniform responses across different environments or crop genotypes (Windari et al., 2021).

Regarding NPK fertilizer rates, the moderate rate of 450 kg ha⁻¹ resulted in the earliest flowering (39.09 DAS), whereas the highest rate of 550 kg ha⁻¹ produced the latest flowering (39.43 DAS). This pattern suggests a non-linear response to mineral nutrition, where moderate nutrient supply may promote a faster reproductive transition, while excessive fertilization tends to stimulate vegetative growth and consequently delay flowering (Oliveira et al., 2021). Although both MLE and NPK significantly affected flowering time, their interaction did not show a consistent cross-level pattern across all treatment combinations.

The results indicate that flowering time was significantly influenced, albeit to a relatively small extent, by MLE concentration and NPK rate, with 7.5%–15% MLE and 450 kg ha⁻¹ NPK tending to slightly accelerate flowering. Although statistically significant, the numerical differences were relatively small and may have limited practical impact under standard production schedules. The effects of MLE appear to be context-dependent and require further validation across multiple environments to determine whether these phenological changes translate into meaningful agronomic benefits.

5. Number of Pods per Plant

Table 5 shows the mean number of pods per plant as influenced by different concentrations of moringa leaf extract (MLE) and NPK fertilizer rates on the growth and yield of common bean plants.

Table 5. Mean number of pods per plant as affected by moringa leaf extract concentration and NPK fertilizer treatments on the growth and yield of common bean plants.

| Moringa oleifera Leaf Extract Concentration (%) | NPK Fertilizer Rate (kg ha ⁻¹) | | | LSD 5% |
|-------------------------------------------------|--------------------------------------------|--------------------------------|---------------------------------|--------|
| | NPK 350 (N1) | NPK 450 (N2) | NPK 550 (N3) | |
| 0 (K0) | 48.07 ^{a_y} | 47.19 ^{b_z} | 48.56 ^{a_{xy}} | 01.10 |
| 5 (K1) | 49.56 ^{a_x} | 48.11 ^{b_z} | 49.00 ^{b_x} | |
| 7.5 (K2) | 49.15 ^{a_{xy}} | 50.11 ^{a_y} | 47.59 ^{b_y} | |
| 15 (K3) | 49.15 ^{b_{xy}} | 51.22 ^{a_x} | 49.30 ^{b_x} | |

Note: Numbers followed by different letters in the rows (a, b, c) and columns (w, x, y, z) indicate significant differences based on the 5% HSD test.

The results in Table 5 indicate that the number of pods per plant was significantly influenced by the interaction between *Moringa oleifera* leaf extract (MLE) concentration and NPK fertilizer rate, with means ranging from 47.19 to 51.22 pods per plant and distinct grouping based on the 5% HSD test. At 0% MLE (K0), the highest pod number was recorded at 550 kg ha⁻¹ NPK (48.56 pods), significantly different from 450 kg ha⁻¹ but not markedly different from 350 kg ha⁻¹, indicating that pod formation does not increase monotonically with NPK alone (Adewusi, 2024). At 5% MLE (K1), the highest value occurred at 350 kg ha⁻¹ NPK (49.56 pods), while 450 kg ha⁻¹ resulted in the lowest response within that treatment level, suggesting that NPK effects are modulated by the background MLE concentration (Sheikha et al., 2022). In contrast, at 7.5% (K2) and 15% MLE (K3), the 450 kg ha⁻¹ NPK rate produced the highest pod numbers (50.11 and 51.22 pods, respectively), indicating a favorable interaction between moderate mineral nutrition and higher biostimulant concentrations (Abdulazeez et al., 2025).

Mechanistically, this pattern supports the concept that MLE functions as a biostimulant that enhances reproductive development when nutrient supply is appropriately balanced. MLE provides amino acids, micronutrients, and growth-regulatory compounds that can influence assimilate partitioning and sink strength, thereby improving pod set under favorable nutrient conditions (Islam et al., 2022). The stronger response observed at 7.5% and 15% MLE in combination with 450 kg ha⁻¹ NPK aligns with the widely reported context-dependent efficacy of biostimulants, which require a compatible nutrient background to maximize yield components (Windari et al., 2021). Conversely, the less consistent response at 0% and 5% MLE across some NPK levels suggests that mineral fertilization alone may not substantially elevate pod production beyond thresholds determined by genotype and environment (El-Dekashey et al., 2022).

The highest mean (51.22 pods) at 15% MLE combined with 450 kg ha⁻¹ NPK indicates a likely synergistic interaction between elevated biostimulant input and balanced mineral nutrition. Similar findings have been reported where reproductive traits improved when biostimulants were integrated with appropriate fertilizer management, reflecting enhanced source–sink dynamics and more efficient resource allocation during pod formation (Karavidas et al., 2022). Nevertheless, variability in biostimulant responses across crops and environments has been emphasized in several studies, underscoring the importance of dose calibration and environment-specific evaluation (Adewusi, 2024).

These findings suggest that optimizing both MLE concentration and NPK rate is essential to maximize pod production. In this study, MLE concentrations of 7.5–15% combined with 450 kg ha⁻¹ NPK frequently produced superior pod numbers, indicating a promising combination for further validation under similar agroecological conditions (Sheikha et al., 2022). However, given the influence of environmental factors such as water availability, pest pressure, and soil characteristics on pod set, site-specific trials remain necessary before generalized recommendations can be established (El-Yazal et al., 2021).

6. Pod Weight per Plant (g)

Table 6 presents the mean pod weight per plant (g) as affected by moringa leaf extract concentration and NPK fertilizer treatments on the growth and yield of common bean plants.

| Moringa oleifera Leaf Extract Concentration (%) | NPK Fertilizer Rate (kg ha ⁻¹) | | | LSD 5% |
|-------------------------------------------------|--------------------------------------------|-----------------------------------|----------------------------------|--------|
| | NPK 350 (N1) | NPK 450 (N2) | NPK 550 (N3) | |
| 0 (K0) | 296.42 ^a _x | 294.01 ^a _z | 302.94 ^a _x | 14.34 |
| 5 (K1) | 305.55 ^a _x | 303.02 ^a _{yz} | 302.96 ^a _x | |
| 7.5 (K2) | 307.90 ^a _x | 317.30 ^a _{xy} | 299.23 ^b _x | |
| 15 (K3) | 303.81 ^b _x | 324.48 ^a _x | 303.60 ^b _x | |

Note: Numbers followed by different letters in the rows (a, b and c) and columns (x, y and z) indicate significant differences based on the 5% HSD test.

Table 6 shows that pod weight per plant was significantly influenced by the interaction between MLE concentration and NPK rate, with values ranging from 294.01 g to 324.48 g per plant. This finding is consistent with previous studies reporting that biostimulants such as MLE tend to be most effective when combined with balanced mineral nutrition, rather than producing uniform effects across all fertilization levels (Windari et al., 2021). At low MLE concentrations (0% and 5%), the response of pod weight to NPK treatments was relatively limited, indicating that at these levels MLE was not yet able to significantly enhance sink strength or reproductive biomass. Similar nutrient-dependent responses have been documented in other studies, where improvements in yield components were observed only under specific fertility conditions (Sheikha et al., 2022).

A clearer interaction pattern emerged at higher MLE concentrations. At 7.5% MLE, the highest pod weight was obtained at 450 kg ha⁻¹ NPK, whereas 550 kg ha⁻¹ resulted in a lower value, suggesting that excessive mineral nutrient supply may reduce the positive effects of biostimulants, possibly due to source–sink imbalances (Karavidas et al., 2022). The strongest response was observed at 15% MLE combined with 450 kg ha⁻¹ NPK, which produced the highest pod weight (324.48 g). This supports the concept of dose-dependent synergy, in which increasing MLE concentration enhances reproductive biomass when paired with moderate and balanced mineral nutrition (Tunc, 2023).

MLE contains amino acids, micronutrients, and hormone-like compounds that can influence flower formation, pod development, and assimilate distribution, thereby increasing pod biomass under favorable nutrient conditions (Mashamaite et al., 2022; Buñay et al., 2023). The increased pod weight observed at higher MLE concentrations with moderate NPK supply indicates that MLE may stimulate reproductive tissue development when nutrients are available in sufficient but not excessive amounts. However, the lack of consistent improvement across all MLE–NPK combinations further confirms that biostimulant performance is highly dependent on environmental and management contexts (Abdulazeez et al., 2025).

The results suggest that maximizing pod biomass in the tested common bean genotype requires proper adjustment of both MLE concentration and NPK rate. The combination of 7.5–15% MLE with 450 kg ha⁻¹ NPK appears most promising under the conditions of this study. Nevertheless, given the significant interaction and the variability reported in the literature, multi-location trials and exploration of wider dose ranges are still necessary to develop more robust and crop and environment-specific recommendations (Banurea et al., 2024).

CONCLUSIONS

Pod weight per plant was significantly affected by the interaction between MLE concentration and NPK rate. The combination of 15% MLE and 450 kg ha⁻¹ NPK produced the highest reproductive biomass, indicating a synergistic effect under balanced nutrient conditions. In contrast, increasing the NPK rate to 550 kg ha⁻¹ did not enhance yield and tended to reduce the effectiveness of MLE.

These results confirm that biostimulant performance strongly depends on nutrient balance; therefore, integrating MLE with appropriate mineral fertilization is essential to maximize productivity. Further trials under diverse environmental conditions are required to strengthen agronomic recommendations.

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