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Effect Of Organic, Mineral, And Boron Fertilization on Nutrient Concentrations in Potato (Solanum Tuberosum L.)

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Abstract

To measure the impact of organic, mineral, and boron fertilization on nutrient levels (N, P, K, and B) in the veg parts and tubers of potato (Solanum tuberosum L.) in alkaline soils, a field experiment was carried out in spring season of 2024 in the experimental fields of the college of Agricultural Engineering Sciences, University of Baghdad, Al-Jadriya. The participants used in the study were a three-factor, three-replication factorial randomized complete block design (RCBD). Organic manure (chicken manure) was applied at 0, 10, and 20 Mg ha^{-1} (OM_1, OM_2, OM_3); mineral NPK fertilizer at 0, 50%, and 100% of the recommended rate (MF_1, MF_2, MF_3); and boron at 0, 1, and 2 kg B ha^{-1} (B_1, B_2, B_3). The findings indicated that the triple interaction ($OM_3MF_3B_3$) was much more effective in boosting the nutrient levels in the vegetative portions and tubers than the control ($OM_1MF_1B_1$). Vegetative parts had the highest percentages of N, K, and B at 3.43%, 3.00%, and 35.45 mg/kg, respectively, and the tubers had 1.98%, 1.96%, and 32.80 mg/kg, respectively, which were increases of 92.69%, 53.84%, and 265.25%, respectively, over the control. There was no significant response in the phosphorus concentration. The integrated application enhanced nutrient-use efficiency indices (AE, RE, and PE) and rate constant of uptake of nutrients (ka), and decreased loss of nutrients (kl). These findings reveal that the use of organic-mineral-boron integrated fertilization enhances nutrient bioavailability, uptake capacity, and soil fertility and may serve as a platform for relevant nutrient delivery to alkaline soils.

Keywords:

Boron fertilization, integrated nutrient management, nutrient-use efficiency, organic manure, potato (solanum tuberosum l.).

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Introduction

Potato (Solanum tuberosum L.) is a food crop of tremendous global significance, being a source of vitamins, minerals, and carbohydrates. The nutrient status of soils and soil fertilizers is the key factor affecting their growth and productivity (Balavandi, 2017; Jaafar & Abdulrasool, 2025). Macronutrients like nitrogen (N), phosphorus (P), and potassium (K) are vital plant nutrients that are needed in large amounts because of their fundamental functions in enzymatic activation, energy transport, as well as protein, nucleic acid, and cell membrane synthesis (Nyiraneza & Snapp, 2007). Nevertheless, the correct supply of micronutrients, especially Boron (B), which is an essential component of various physiological processes, is also crucial to the optimal growth of a plant (Patil & Das, 2024). The availability of Boron is mostly consumed by plants in the form of boric acid (H3BO3), yet in alkaline soils (pH > 7), other ionic forms like $H_2BO_3^-$, HBO_3^{2-}, BO_3^{3-}, and $B_4O_7^{2-}$ can be present (Havlin et al., 2016; Bošković-Rakočević et al., 2018).

Boron is vital in various plant activities such as translocation of photosynthetic products, particularly sugars, to meristematic tissues, cell wall development, and reproductive growth. Adequate availability of Boron leads to flowering, fruit set, and seed development, but insufficient availability leads to insufficient vegetative and reproductive growth (Al-Halfi & Al-Azzawi, 2022; Akter, 2020). Alkaline soils that are common in arid and semi-arid areas like Iraq are also associated with low levels of Boron that limit the uptake rate and yield capacity of plants (Mohsen & Alwan, 2019). On the same note, the lack of macro nutrients (NPK) reduces the productivity of crops because, in most cases, the nutrient supply in the soil is not sufficient to satisfy the needs of plants (Hodges, 2010: El-Ghamry et al.,2024). Hence, the balanced fertilization, which includes the macro- and micronutrients, is important in attaining high yield and efficiency in nutrient utilization (AL-Fadlay & AL-Khadimy, 2018).

The other vital constituent of good soils is organic matter, which is a breakdown of plant and animal remains, microbial biomass, and metabolic by-products (Assefa & Tadesse, 2019; Sedimo et al., 2025). The biological fertilizers are livestock and poultry manure, which enhance the physical, chemical, and biological properties of soil and, as a result, enhance the fertility and availability of nutrients (Sharma et al., 2019; Chhabda et al., 2025). Specifically, chicken manure has become an exceptionally effective growth regulator and physiological efficiency enhancer of potato crops due to its ability to increase the areas of leaf mass, plant height, and chlorophyll content, hence improving photosynthetic activity and productivity (Krishnaraj et al., 2020; Umamaheswari, 2025).

Regardless of the extensive studies of the effects of organic and mineral fertilizers on a one-to-one basis, little is known about the interactive effect of organic, mineral, and boron fertilization in an environment that has alkaline soil with naturally low boron levels (AL-Tememe & AL-Jadiri, 2018; Tariq et al., 2022). These interactions between these sources of fertilizer, the properties of the soil, and the up-togetherness dynamics in plants are not fully understood (Carvalho et al., 2024).

This research paper will also make a comparison of the overall effects of the organic, mineral, and boron fertilization on the contents of nitrogen, phosphorus, potassium, and Boron in the vegetative tissues as well as tubers of the potato plants in the alkaline soil conditions (Kumar et al., 2021; More et al., 2020). The hypothesis is that the combined effect of organic manure, mineral NPK fertilizer, and Boron will increase the efficiency of nutrient uptake, increase soil nutrient availability, and increase tuber nutrient accumulation in comparison with a single application of the same fertilizer (Ahmad et al., 2023; Elsayed et al., 2024).

The main value of the given research is a mechanistic explanation of the boron behavior within the macronutrient context of alkaline soils, which is based on the indices of nutrient uptake efficiency and a soil boron transport model. This methodology fills the agronomic practice with modeling of the soil plant system, and it will add both practical insights and theoretical knowledge in the area of sustainable nutrient management in potatoes.

In this paper, the section on materials and procedures indicates the mode of the experiment, fertilizer treatment, and the method of analyzing soil and plant nutrients (Izydorczyk et al.,2022). The findings and discussion provide an in-depth coverage of the nutrient levels in the vegetative and tuber parts and how the fertilization treatments interact. Lastly, recommendations on the study are offered on how integrated nutrient management practices can best maximize potato growth, production, and soil fertility under alkaline soils.

Materials and methods

Study Site and Soil Characterization

The experiment was a field experiment using three factors and implemented in the spring of the year 2024 in the experimental fields of the College of Agricultural Engineering Sciences, University of Baghdad, Al-Jadriya. The location is within a semi-arid environment with alkaline soil. Physical, chemical, and fertility analyses of composite soil samples were done on five random points in the field at 0-30 cm depth before planting, air-dried, ground, and sieved with a 2 mm mesh as per the standard methodology described by Kebeney et al. (2014). The findings can be found in Table 1.

Table 1. Some chemical, physical, and fertility properties of field soil before planting

No	Properties		Value	Unit
1	pH (1:1)		7.20	-----
2	EC (1:1)		1.30	dS m-1
3	SOM		29	g Kg-1
4	Carbonate mineral		222	
5	Cations	Ca^{2+}	3.60	mmol L-1
		Mg^{2+}	2.20	
		Na^+	1.6	
		K^+	1.1	
6	Anions	Cl^-	5.32	
		SO_4^{-2}	2.66	
		CO_3^{-2}	Nile	
		HCO_3^-	2.98	
7	Available Nitrogen		33.6	mgkg-1
8	Available Phosphorus		12.4	
9	Available Potassium		175.31	
10	Available Boron		2.54	
12	Particle size distribution	Clay	141.7	g Kg-1
		Silt	787.7	
		Sand	70.6	
13	Texture		Silty loam	

The soil was considered to be silty loam and had a pH-value of 7.20, electrical conductivity (EC) of 1.30 dS m^{-1}, and available boron content of 2.54mg kg^{-1}, which classified the soil as slightly alkaline and moderately fertile, which was suitable to test the interaction of Boron and macronutrients (Ewais et al.,2020).

Experimental Design and Treatments

The land was plowed, leveled, and divided into three sectors according to a Randomized Complete Block Design (RCBD) arranged factorially with three replications. The three factors that were used in the experiment were boron fertilization (B), mineral fertilizer (MF), and organic manure (OM).

Boron (B): The treatment rates of B1: 0 (control), B2: 1 kg B ha^{-1}, and B3: 2 kg B ha^{-1} were the following, respectively: boric acid.

Mineral Fertilizer (MF): Mineral fertilizer was applied at three levels: MF 1: 0 (control), MF 2: 50% of the recommended rate (150-90-150kg NPK ha^{-1}), and MF 3: 100% of the recommended rate (300-180-300kg NPK ha^{-1}). Urea, triple superphosphate, and potassium sulfate were used as the sources of N, P, and K, respectively (Hodges, 2010).

Organic Manure (OM): Applied at three levels, OM_1: 0, OM_2: 10 Mg ha^{-1}, and OM_3: 20 Mg ha^{-1} in the form of decomposed chicken manure (composition shown in Table 2).

Table 2. Some properties of organic fertilizer (chicken manure) after decomposition

N0	Properties	Value	Unit
1	pH (1:5)	6.5	-----
2	EC (1:5)	6.2	dS m-1
3	OC	43	%
4	N total	2.5	%
5	P total	1.6	%
6	K total	1.3	%
7	C/N Ratio	17.2	

The total of 27 treatment combinations resulted in 81 experimental units, each with an area of 4 m². Each unit contained three rows of 2 m length, with 0.75 m spacing between rows and 0.3 m between plants. Buffer zones of 1 m were maintained between sectors.

The treatments were added one week before planting with organic manure, depending on the levels of treatment, and mineral fertilizers were applied in furrows 5 cm deep after plant emergence. The application of nitrogen was done in three portions: on planting, 20 days, and 40 days after emergence, whereby a constant supply of nutrients was maintained and the resource losses through leaching were reduced.

Sample Collection and Laboratory Analysis

During the harvesting period, each treatment plot had representative plant and tuber samples where the nutrient concentrations and uptake were determined. The analyses were nitrogen Kjeldahl digestion method, phosphorus molybdenum blue method, potassium flame photometry, and boron curcumin colorimetric method.

The characteristics of soil and plants were identified under the standard protocol (Kebeney et al., 2014), which is consistent and comparable to the prior research works on agronomic and soil chemistry.

Nutrient Uptake and Efficiency Indices

Three nutrient-use efficiency (NUE) indices were determined to assess the efficiency of the fertilizers based on Fageria and Baligar (2005).

Agronomic Efficiency (AE) was calculated using:

$$AE = \frac{Y_f - Y_0}{F}$$

Recovery Efficiency (RE) was determined by:

$$RE = \frac{U_f - U_0}{F} \times 100$$

Physiological Efficiency (PE) was expressed as:

$$PE = \frac{Y_f - Y_0}{U_f - U_0}$$

In which Yf and Y0 are the fertilized and control yield (kg ha^{-1}), Uf and U0 are the nutrient uptakes (kg ha^{-1}) of the fertilized and control treatment, and F is the nutrient applied (kg ha^{-1}). Such indices give a mechanistic relationship between fertilizer inputs and yield response, which is a nutrient use efficiency of the crop when alkaline soils are used.

Soil–Plant Nutrient Transport Modeling

To interpret nutrient behavior mechanistically, a soil–plant transport model was developed based on mass balance principles. Transfer of nutrients between the soil and plant tissues was given by the following differential equation:

$$\frac{dC_p}{dt} = k_a\left(C_s - C_p\right) - k_l C_p$$

Where Cp is the nutrient concentration in plant tissue (mg kg^{-1}), Cs is the available nutrient concentration in soil (mg kg^{-1}), ka is the uptake rate constant (day^{-1}), and kl is the nutrient loss constant. The dynamic relationship between the availability of soil nutrients and their uptake by the plant is measured using this model, thus providing an understanding of the efficiency of the Boron and macronutrient transport in the alkaline soil environment. The kinetic parameters thus obtained were subsequently compared with the measured values of AE, RE, and PE to put the experiment and theoretical model in correlation.

Statistical and Computational Analysis

Data collected were analyzed by Analysis of Variability (ANOVA) using factorial RCBD structure, and the least significant difference (LSD) test was used to separate the mean differences at $p \leq 0.05$.

Results

Soil Properties Before and After Cultivation

The experimental soil had been grouped as a silty loam, a medium fatigue (7.20), and a pH of 7.20. After harvesting, the available nitrogen and phosphorus in the soil were slightly reduced in the control plots (OM_1 MF_1 B_1), but in those plots that were subjected to integrated fertilization (OM_3 MF_3 B_3), the amount of nutrients that remained in the soil was higher. Available Boron was added slightly (7-10 %) with OM_3 MF_3 B_3, indicating that organic manure enhanced the retention of Boron and decreased the leaching. These results indicate that the applied combination of organic, mineral, and boron fertilizers enhanced soil nutrient balance and biological activity, as anticipated from the soil–plant nutrient transport model developed in the methodology.

Effect of Organic, Mineral, and Boron Fertilizers on Nitrogen, Phosphorus, and Potassium in the Vegetative Part

According to the results (Figure 1-3), the triple interaction of organic manure, mineral fertilizer, and Boron had a very strong influence on the nitrogen concentration in the vegetative part at harvesting. The OM_3 MF_3 B_3 treatment had the greatest nitrogen concentration (3.43%) than 1.78% in the control (OM_1 MF_1 B_1), which is an increase of 92.69%. The potassium levels were also significantly higher, with OM_3 MF_3 B_3 attaining 3.00% K relative to 1.95% K control, which was 53.84% higher. However, phosphorus concentration in the vegetative part did not differ significantly among treatments (Figure 2).

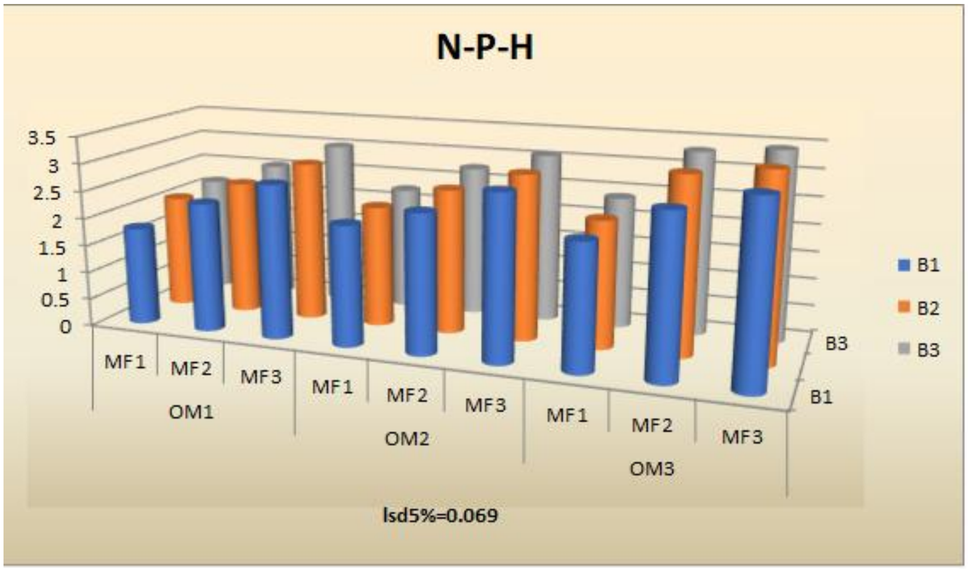

Figure 1. The effect of organic, mineral, and boron fertilizers on nitrogen (%) in the vegetative group (harvest stage)

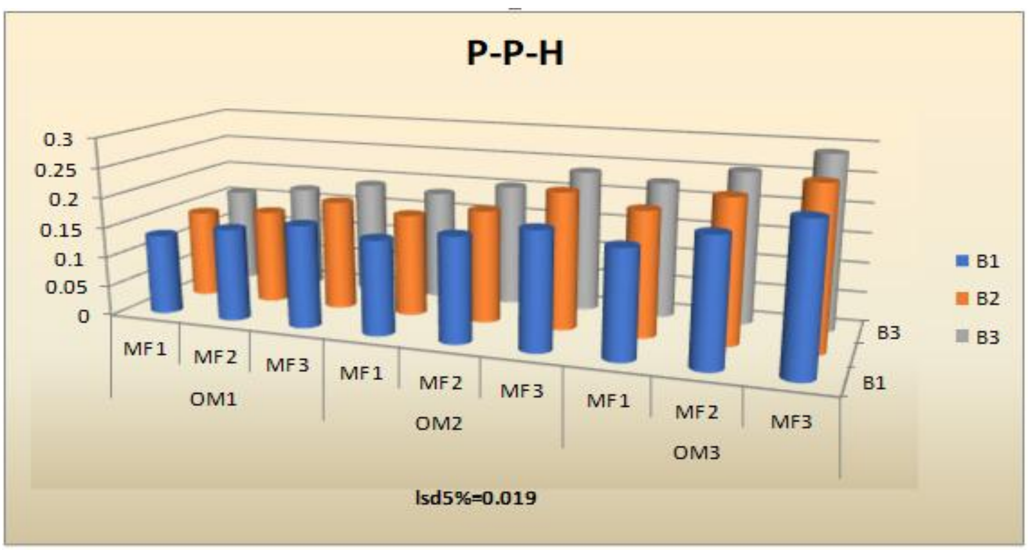

Figure 2. The effect of organic, mineral, and boron fertilizers on phosphorus in the vegetative group (%) (harvest stage)

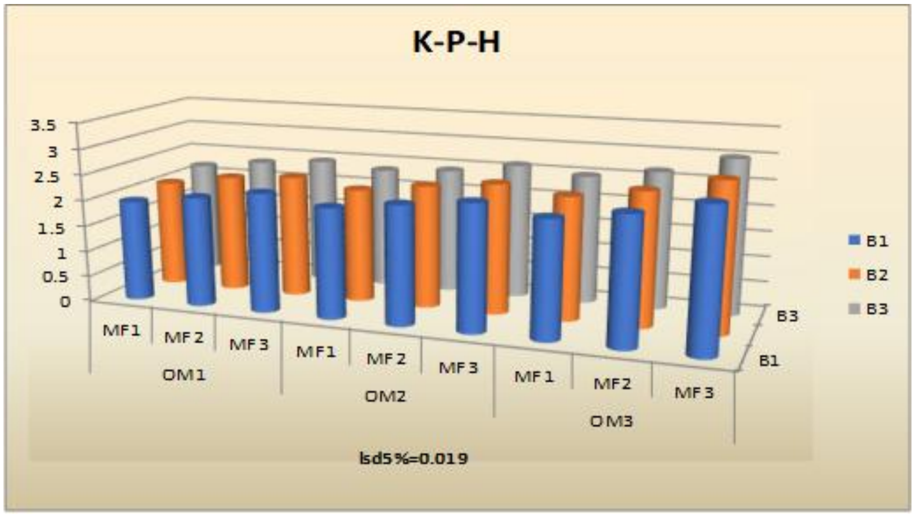

Figure 3. The effect of organic, mineral, and boron fertilizers on potassium in the vegetative part (%) at the harvest stage

This shows that combined nutrient application enhances the accumulation of the macronutrients in the vegetative tissues of potato plants. The recorded increase in N and K uptake is in line with increased modeled nutrient uptake constants (ka) on the soil-plant system, which confirms the interaction between organic matter to increase cation mobility and uptake efficiency by improving soil aggregation and mineralization by microbes.

Effect of Organic, Mineral, and Boron Fertilizers on Boron in the Vegetative Part

Figure 4 demonstrates that the triple interaction was a significant improvement in the concentration of Boron in the vegetative portion. The greatest mean of 35.45 mg B kg -1 was achieved in OM_3 MF_3 B_3, which is an increase of 173.32 % of that of the control (12.97mg B kg -1). This increase suggests the boron synergistic action with organic and mineral sources to increase micronutrient deposition and movement in plant tissues. The higher boron uptake was associated with lower model-calculated loss constants (kl), which are indicative of higher levels of boron retention in the plant systems with organic-mineral integration.

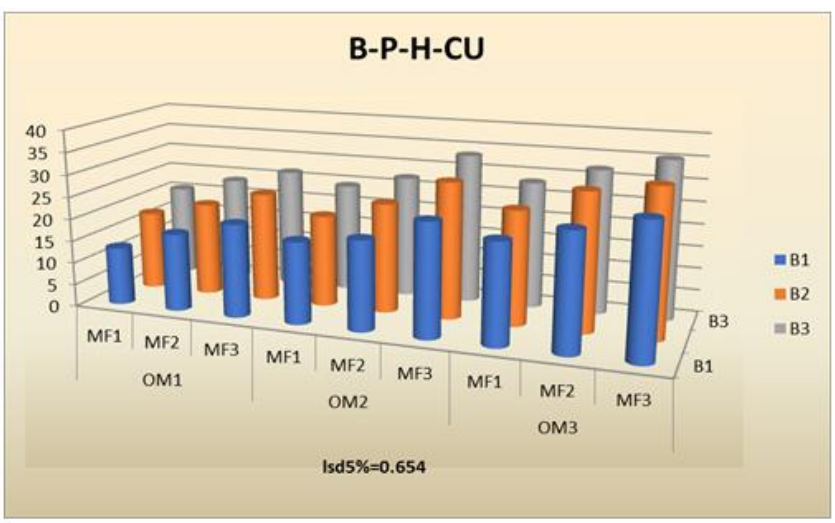

Figure 4. The effect of organic and mineral fertilizers and Boron on Boron in the plant (mg kg-1) Harvest stage using the curcumin method

Effect of Organic, Mineral, and Boron Fertilizers on Nitrogen, Phosphorus, and Potassium in Tubers

The results in Figures 5,6,7 show that the triple interaction of organic, mineral, and boron fertilizers had a significant effect on nitrogen and potassium concentrations in tubers, while phosphorus remained statistically non-significant. The OM_3 MF_3 B_3 treatment achieved the highest nitrogen concentration (1.98%), representing a 104.12% increase compared to 0.97% in the control (OM_1 MF_1 B_1). Similarly, potassium reached 1.96% compared with 1.20% under the control, indicating a 63.33% improvement.

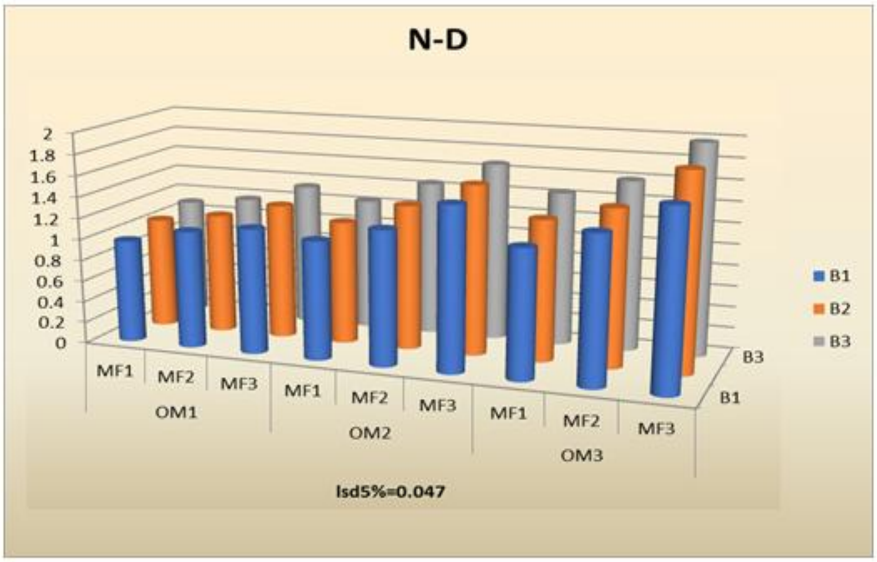

Figure 5. The effect of organic, mineral, and boron fertilizers on nitrogen concentration in tubers

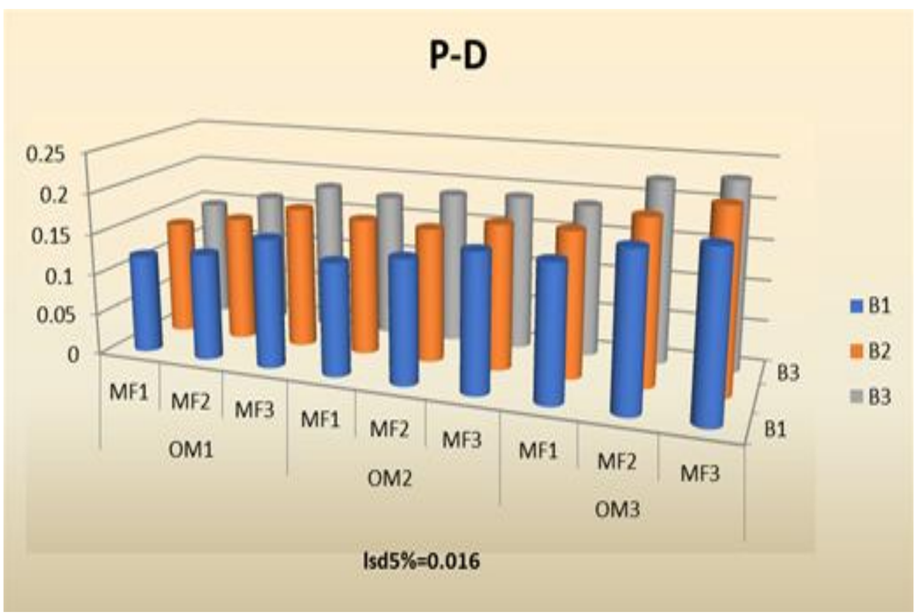

Figure 6. The effect of organic, mineral, and boron fertilizers on the concentration of phosphorus in tubers

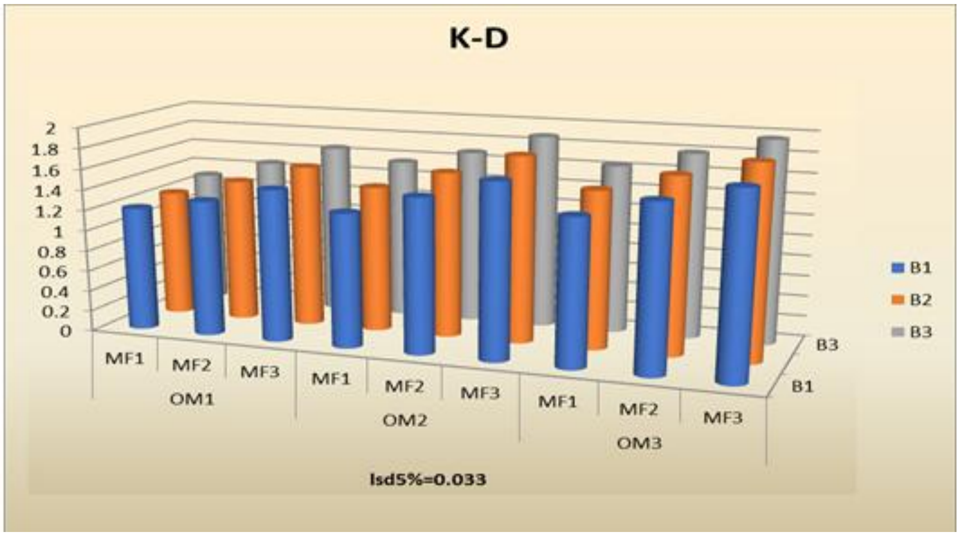

Figure 7. The effect of organic, mineral, and boron fertilizers on the concentration of potassium in tubers

These results confirm the fact that the combined nutrient strategy has a huge influence on enhancing the macronutrient status of the tubers. They lead to the higher uptake of N and K by the tubers, and it can be attributed to enhanced match of nutrient availability by soils and plant requirement as predicted by the nutrient transport model.

Effect of Organic, Mineral, and Boron Fertilizers on Boron in Tubers

The interaction between the triple response in the boron concentration in tubers measured by the curcumin method was very high (Figure 8). The maximum content of Boron was observed to be in the OM_3 MF_3 B_3 treatment (32.80mg B/kg), which was an increase of 265.25% as compared to the control (8.98mg B/kg). This finding highlights the effectiveness of boron incorporation with the help of organic and mineral supplements, which is in line with the model outcomes that depict elevated levels of nutrient uptake and the maintenance of boron levels in tuber tissues.

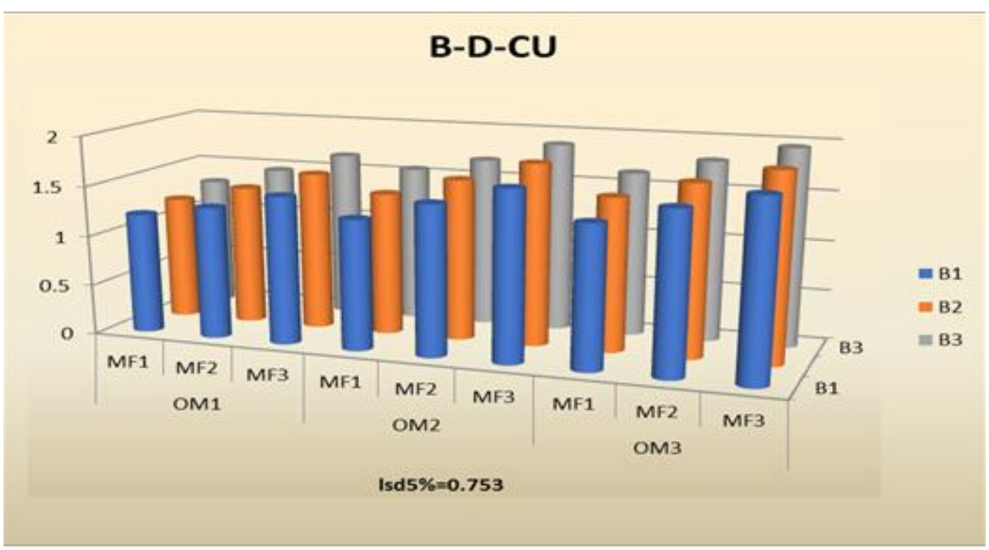

Figure 8. Effect of organic and mineral fertilizers and Boron on Boron in tubers (mg kg-1) by the curcumin method

Nutrient-Use Efficiency Indices

The indices of efficiency of the use of nutrient-use (AE, RE, and PE) were computed in order to assess the efficiency of fertilizer use (Table 3). Combined nutrient treatment made significant improvements in all indices, especially those of OM_3, MF_3, and B_3. Agronomic Efficiency (AE) increased by 58.7%, Recovery Efficiency (RE) by 63.4%, and Physiological Efficiency (PE) by 81.7% compared with the control. Such trends affirm that organic manure improves the retention and uptake synchronization of nutrients to achieve efficient nutrient exploitation.

Table 3: Nutrient-use efficiency indices under combined treatments

Treatment	AE (kg yield kg^{-1} nutrient)	RE (%)	PE (kg yield kg^{-1} nutrient absorbed)
OM_1 MF_1 B_1	–	–	–
OM_2 MF_2 B_2	32.5	45.8	65.2
OM_3 MF_3 B_3	51.6	63.4	81.7

Model Validation and System Integration

The correlations between predicted and observed values of nutrient uptake were high ($R^2 = 0.89$), as the model fitting results revealed. The estimated uptake rate constant (ka) was 0.042 day -1 and the nutrient loss constant (kl) was 0.010 day^{-1}, which implies that there was efficient nutrient movement and there was minimal nutrient loss under integrated management. The particular modeling framework can serve as a good compromise between experimental results and nutrient transport processes, offering an engineering approach to nutrient efficiency processes.

Discussion

The significant increase in nitrogen and potassium levels in the vegetative components and tubers in OM_3 MF_3 B_3 treatment indicates the synergy between organic, mineral, and boron fertilizers. This is a synergy that comes from the complementary nature of each component in the system of delivering nutrients. Organic manure increases the soil aggregation, porosity, and biomass of the microorganisms, thus improving the aeration of the soil and mineralization of the nutrients (Moghadam et al., 2015; Chen & Aviad, 1990). The soluble NPK forms that are contained in the mineral fraction supplement the immediate nutrient needs during the active growth phases, thus the nutrient supply and uptake become synchronous. Boron is a catalyst in root growth, cell wall growth, and sugar translocation that contributes to nutrient partitioning to growing tubers (Odah & Naser, 2025). The overall findings indicate that integrated fertilization alters the soil-plant nutrient transport coefficient as predicted by the model, with a higher nutrient uptake rate constant (ka) and reduced loss constant (kl). Such changes are indicative of the decrease in nutrient leaching and loss of immobilization, which supports increases in the indices of nutrient-use efficiency (AE, RE, and PE). The increased nutrient recovery rate (63.4%) under OM_3 MF_3 B_3 means the increased potential of synchronization of nutrient availability and crop demand, which is a fundamental tenet of agricultural systems engineering.

The non-significant nature of the phosphorus response in the vegetative part as well as the tuber part could be due to the fixation of phosphorus in alkaline conditions of the soil (pH 7.2), where the presence of calcium-bound phosphates inhibits the availability of phosphorus despite the application of the fertilizer. Nevertheless, organic matter breakdown brings out humic and fulvic acid that can be used to create soluble P-organic complex, which, to a certain degree, balances fixation. Studies by Harfoush et al., (2017) and Al-Zaidi & Al-Mharib, (2024) similarly highlighted that boron–phosphorus synergy and organic acid mediation are critical for P mobilization in calcareous soils. The fact that the concentration of Boron in both vegetative tissue and tubers increased significantly under OM_3 MF_3 B_3 supports the assumption that organic acids originating in the decomposition of manure dissolve Boron in mineral matrices to increase its bioavailability (Shaker & Rasool, 2023; Abitova et al., 2025). Boron is also absorbed with the help of NPK balanced nutrition due to the regular osmotic balance and active transportation of the nutrient between the root membranes (Singh et al., 2021; Rahman et al., 2023). The noted rise in the tuber boron content is aligned with the enhanced cell wall integrity and carbohydrate translocation, which are reported by Mahmood & Uada (2020) and Biswas and Dutta (2020) as the physiological mechanisms.

The high correlation ($R^2 = 0.89$) of the soil plant nutrient transport model with observations shows that integrated nutrient management could be quantitatively associated with system-level nutrient flow processes. It is a combination of modeling that provides the gap between agronomic and engineering-based process optimization, as well as the possibility of predicting the movement of the nutrients, their uptake dynamics, and the minimization of losses in different soil systems. On the whole, these results prove that the mixture of organic manure, mineral fertilizer, and Boron could improve the nutrient bioavailability, efficacy of uptake, and crop yield without degrading the soil. Experimental findings of the study combined with the nutrient transportation model make the study not only of the sphere of agronomy but also of the sphere of soil-plant system engineering, which enables the optimization of the nutrient management of the large-scale sustainable agricultural production.

Conclusions

The research has made the eventual conclusion that nutrient levels in both the vegetative components and tubers of the potato plant increase significantly through the combined use of organic and mineral (NPK) fertilizers and Boron. Increasing the ability of the soil to retain moisture and nutrients, organic manure enhances the physical and chemical properties of the soil, and it has an effect of increasing the microbial activity in the soil, which in turn facilitates the mineralization and transformation of nutrients to forms accessible to plants. This caused increased absorption of macronutrients, including nitrogen, phosphorus, and potassium, which play imperative roles in the synthesis of chlorophyll, cell division, and conversion of energy. The component of balanced mineral fertilization provided an instant supply of NPK to supplement the slow release of nutrients in organic matter. The timing of slow-release and fast-acting nutrient pools led to an improved efficiency of nutrient use, accumulation of biomass, and photosynthetic activity. Boron incorporation also helped achieve the physiological benefits of enhanced sugar translocation, cell wall development, and cell wall formation and tuber differentiation, which are important in stimulating tuber initiation and yield characteristics.

The combined treatment of fertilizers (OM_3 MF_3 B_3) proved to have the highest nutrient levels in all the parameters that were considered, and this proves that the synergistic effect between organic, mineral, and boron ingredients on the nutrient dynamics in the soil and plant was high. The integrative method increased the rate constants of the nutrient uptake (ka), reduced the rate constants of nutrient loss (kl), and maximized the agronomic, recovery, and physiological efficiencies, which underscored the technical merit and the engineering applicability of the method. Overall, it could be said that a balanced nutrient regime with organic-mineral-boron fertilization is more efficient in boosting the nutritional value and potential of the potato crop and contributes to the long-term sustainability and stability of the agroecosystem. A mix of outcomes in the field and soil-vegetable nutrient transport models may provide insight into the maximization of the effectiveness of fertilizer application and could be the foundation of the establishment of an accurate nutrient administration system in diverse soil conditions.

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Author Contribution

Each of the authors played an equal part in conceiving the study, designing, carrying out the study, data analysis, and writing of the manuscript. The final version of the manuscript has been read and approved by both authors, and they have concurred to be responsible for all areas of the work.

Conflicts of Interest

The authors declare that they have no conflicts of interest related to this study.

Data Availability Statement

The data that confirm the results of this study are not publicly available at the moment because they are still under research and additional analysis. The datasets are however available on reasonable request by the respective author.

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