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Impact of Macro and Micro-Nutrient Omission on Maize Growth and Yield: Assessing Critical Limiting Factors in Nutrient Management

Elli Afrida*, Magdalena Saragih, Abdul Rahman

Program Study of Agrotechnology, Faculty of Agriculture, Universitas Medan Area, Medan 20223, Indonesia

Corresponding Author Email: elliafrida@staff.uma.ac.id

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ABSTRACT

Deficiency in both macro and micro-nutrients can disrupt the metabolic processes of plants, leading to a decline in maize yields. This study aimed to: (1) assess the impact of omitting specific macro-micro nutrients on maize growth and yield, (2) identify the relationship between maize growth and yield under nutrient omission conditions, and (3) determine the sequence of nutrients that are the most critical limiting factors for maize yield. The research was conducted on farmers' fields in Medan Selayang, North Sumatra, Indonesia, from May to September 2023, utilizing nutrient omission techniques tailored to the requirements of maize plants. The experiment followed a Completely Randomized Block Design with a single factor—the removal of nutrients N, P, K, Ca, Mg, S, Mn, Zn, Fe, and Cu. Data were analyzed using ANOVA and tested with DMRT at P<0.05, followed by correlation analysis. The results indicated that maize growth and yield were inhibited by 29.44-66.03% and 20.11-49.18%, respectively, in the absence of nitrogen fertilization. Maize productivity was significantly influenced by leaf area, total chlorophyll content, root length, root volume, and the dry weight of both shoots and roots. The sequence of nutrient importance as limiting factors for maize productivity was identified as follows: N < K < S < Ca < Fe < P < Zn < Mg < Mn < Cu.

1. INTRODUCTION

Macronutrients play a pivotal role in the metabolic activities of maize, directly influencing physiological and biochemical processes that determine plant growth and yield. Nitrogen (N) application has been shown to enhance the photosynthesis rate and nitrogen use efficiency in maize, as highlighted by Ma and Biswas [1]. Moreover, the combination of nitrogen and phosphorus (P) fertilizers has been found to significantly boost grain production, total biomass, and nitrogen uptake in maize grains [2]. In their study, Ray et al. [3] demonstrated that the application of N+P_2O_5 at 200+60 kg ha^{-1} resulted in a remarkable increase in maize grain protein content by 10.08% compared to other nutrient combinations, such as P_2O_5+K_2O and N+K_2O at different rates. Furthermore, the use of urea, TSP, and potassium at a combined dose of 160+54+0 kg ha^{-1} significantly increased plant height, as observed by Hermanuddin et al. [4]. Similarly, Mohammed et al. [5] reported that an N+P fertilization rate of 64+20 kg ha^{-1} led to a significant increase in maize plant height compared to applying these nutrients individually. Additionally, research by Zhang et al. [6] has shown that the photosynthesis rate under NP fertilization surpasses that of PK and NK fertilization, emphasizing the crucial role of balanced macronutrient application.

The leaf area and nutrient uptake are critical indicators of maize plants' photosynthetic efficiency, directly impacting biomass production and yield. The absence of adequate nitrogen and phosphorus application can result in reduced grain weight, indicating the importance of these nutrients for optimal plant development [7]. The study by Wang et al. [8] revealed that using a NO_3^-/NH_4^+ ratio of 75:25 can significantly increase ATP production, photosynthesis rate, and total carbon content, as well as improve the uptake of N, P, Cu, and Fe in maize plants. Furthermore, Qiu et al. [9] noted that maximum grain yield was achieved with a nitrogen application rate of 210 kg ha^{-1}. Lamptey et al. [10] suggested an optimal nitrogen fertilization rate for maize in summer, ranging from 200 to 300 kg ha^{-1}. However, Flores-Sánchez et al. [11] found that P and K nutrients were not typically limiting factors in maize production, with nitrogen being more critical due to the soil contributing only 11% of the total nitrogen availability.

In addition to macronutrients, micronutrients, though required in smaller quantities, are vital for the proper growth and yield of maize. Engels et al. [12] emphasized that even minor deficiencies in micronutrients during specific growth stages could significantly impact grain yield. For instance, Stewart et al. [13] found that applying Fe fertilizer at a dose of 0.22 kg ha^{-1} during critical stages such as V6 to R2 resulted in a significant increase in grain yield. Bender et al. [14] noted that to achieve a maize biomass of 23 tons ha^{-1} with a productivity of 12 tons ha^{-1}, the plant roots must uptake adequate amounts of Fe and Zn. Conversely, nutrient deficiencies, particularly in Fe and Zn, can lead to a 40% reduction in growth and yield, as plants struggle with inefficient nutrient transport within the xylem [15, 16].

Given the significant influence of both macro- and micronutrients on maize development, assessing the limiting factors in nutrient availability is crucial, particularly for fields under continuous cultivation. Nutrient omission techniques can be employed to identify these limiting factors by observing specific plant responses such as reduced height, delayed maturation, smaller seed size, and leaf chlorosis or necrosis [17]. Prior studies, including those by Tampubolon et al. [18] and Afrida and Tampubolon [19], have indicated that nitrogen is the primary limiting factor affecting maize growth, more so than phosphorus and potassium. However, these studies were limited to major macronutrients and did not encompass a broader spectrum of macro (N, P, K, Ca, Mg, S) and micro (Mn, Zn, Fe, Cu) nutrients across the entire growth phase.

Comprehensive studies that encompass the effects of both macro- and micronutrients during the vegetative and generative stages of maize are essential for a more holistic understanding. Employing nutrient omission techniques in fertilization studies can serve as a valuable reference for improving maize yields and effective nutrient management. Therefore, this study aims to (1) evaluate the impact of omitting various macro- and micronutrients on maize growth and yield, (2) examine the relationship between maize growth and yield under nutrient omission, and (3) identify the sequence of nutrients that act as critical limiting factors for maize yield. By addressing these goals, this research contributes to a deeper understanding of nutrient management in maize cultivation, offering insights that can guide practical fertilization strategies to optimize crop production.

2. MATERIALS AND METHODS

2.1 Study location and initial soil analysis

The study was conducted in a farmer's field located in Medan Selayang, North Sumatra, Indonesia (3°33.669' N, 98°38.832' E) from May to September 2023. To ensure accurate representation of the soil conditions, topsoil was collected from Namorih Village, Pancur Batu Subdistrict, Deli Serdang District (3°30'09.8" N, 98°35'01.7" E). The soil samples were gathered from a depth of 0-20 cm, ensuring uniformity in the growing medium. Before use, soil samples underwent comprehensive chemical analysis. Soil pH was measured using the potentiometric method with a glass electrode in a 1:2.5 soil-to-water suspension. Cation Exchange Capacity (CEC) and Base Saturation (BS) were determined using the ammonium acetate method at pH 7.0, as outlined by the Indonesia Soil Research Institute (2005). The soil was found to be acidic with a pH of 4.53, had a moderate CEC of 24.05 me/100 g, and a very low BS of 9.29%. The soil's texture, organic matter content, and macro- and micronutrient levels were also analyzed to provide a baseline for the nutrient omission study.

2.2 Growing media preparation and experimental design

The collected soil was air-dried and sieved through a 2 mm mesh to remove debris and larger particles. The prepared soil was then homogenized and filled into 20 kg capacity polybags with a diameter of 34 cm and height of 54.5 cm. Each polybag was filled with an equal weight of soil to ensure uniform growing conditions. The experiment followed a Completely Randomized Block Design (CRBD) with a single factor, arranged in a 3 × 12 factorial structure. Treatments were laid out in a grid with a spacing of 70 cm × 30 cm to minimize competition for light, water, and nutrients. Each treatment was replicated three times to ensure statistical validity. The superior maize variety, BISI-79, was used for this study due to its known responsiveness to nutrient management (Figure 1).

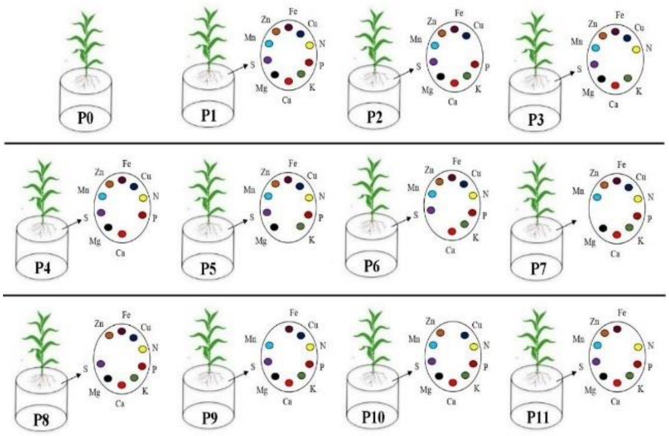

Figure 1. Overview of nutrient omission techniques utilized in the study

Note: Treatments include: P0 = Control (no nutrient omission), P1 = Complete fertilization (all nutrients provided), P2 = Nitrogen omission (-N), P3 = Phosphorus omission (-P), P4 = Potassium omission (-K), P5 = Calcium omission (-Ca), P6 = Magnesium omission (-Mg), P7 = Sulfur omission (-S), P8 = Manganese omission (-Mn), P9 = Zinc omission (-Zn), P10 = Iron omission (-Fe), and P11 = Copper omission (-Cu).

Two seeds were planted per polybag, and after germination, one seedling with optimal growth was retained to ensure uniform plant density. Basic fertilization with NPK Mutiara at 150 kg ha^{-1} was applied as a starter to provide essential nutrients during the initial growth phase.

2.3 Nutrient omission techniques

This study employed nutrient omission techniques to isolate the effect of each macro- and micronutrient on maize growth. The macronutrients (N, P, K, Ca, Mg, S) and micronutrients (Mn, Zn, Fe, Cu) were selected based on their known importance in maize nutrition. The nutrient requirements for maize were adapted from Olson and Sander and included the following target doses: N (129 kg ha^{-1}), P (31 kg ha^{-1}), K (39 kg ha^{-1}), Ca (1.1 kg ha^{-1}), Mg (11 kg ha^{-1}), S (12 kg ha^{-1}), Mn (0.06 kg ha^{-1}), Zn (0.19 kg ha^{-1}), Fe (0.11 kg ha^{-1}), and Cu (0.02 kg ha^{-1}). These doses were recalculated based on the soil's weight and volume in the polybags and then converted into the corresponding fertilizer forms. Each nutrient was omitted one at a time from the fertilization scheme to create individual treatments. Fertilizers were weighed with an analytical scale to ensure precision. Application involved carefully mixing the fertilizers into the soil to a depth of 1 cm around the plants to facilitate root uptake. Nutrient omission was applied at both the early vegetative (V4) and generative (R1) stages to observe effects throughout the maize growth cycle.

2.4 Plant management and data collection

Throughout the experiment, plant health was managed using integrated pest and disease management practices. An insecticide (deltamethrin 25 g L^{-1}) and a fungicide (mancozeb 80%) were applied at recommended doses to control pests and diseases. Agronomic characteristics such as plant height, number of leaves, leaf area, and SPAD chlorophyll index were measured monthly. Leaf area was calculated using the formula:

$$L = p \times l \times k$$

where, L is the leaf area, p is the leaf length, l is the leaf width, and k is the correction factor (0.75 as per studies [13, 20]). Leaf length and width were measured using a caliper to ensure accuracy. Total chlorophyll content was assessed using a SPAD-502 chlorophyll meter, focusing on the second fully expanded leaf from the top, which is an indicator of the plant's overall health and nutrient status.

At the end of the growing season, harvest was conducted when approximately 80% of the maize husks had turned brown, indicating physiological maturity. Measurements included flowering and harvesting age, root length and volume, root-to-shoot ratio, fresh and dry weights of shoots and roots, cob stalk length, cob length, husk weight, cob weight, seed number, seed weight, 100-seed weight, and overall yield. Fresh weights were measured immediately after harvest using a precision balance. For dry weight determination, plant parts were oven-dried at 80°C for 24 hours to constant weight.

2.5 Data analysis

Data were subjected to statistical analysis using Analysis of Variance (ANOVA) to determine the significance of treatment effects on maize growth and yield. Duncan's Multiple Range Test (DMRT) at $P<0.05$ was employed for mean separation to identify specific differences among treatments. In addition, correlation analysis was conducted to assess the relationships between growth parameters and yield characteristics, utilizing IBM SPSS Statistics 20 software [21]. This comprehensive approach provided insights into the nutrient-specific effects on maize performance, allowing for a detailed interpretation of how nutrient omissions impact plant development and productivity.

3. RESULT

The application of nutrient omission techniques demonstrated a substantial impact on several key agronomic characteristics of maize plants, particularly influencing parameters such as leaf area, total chlorophyll content, overall biomass, and root morphology, including both length and volume. However, the data indicated that plant height, the number of leaves, and the root-to-shoot ratio were relatively unaffected by these treatments, suggesting a selective influence of nutrient omissions on maize growth dynamics. Among the various nutrient omission treatments, the absence of nitrogen (P2) proved to be the most detrimental to plant growth. Specifically, nitrogen omission led to a considerable reduction in several growth parameters. The leaf area was reduced by approximately 50.53%, indicating a significant impairment in the plant's photosynthetic capacity, as leaf area is directly associated with the ability to capture sunlight and perform photosynthesis. Additionally, the total chlorophyll content decreased by 29.44%, further confirming the crucial role of nitrogen in chlorophyll synthesis and overall photosynthetic efficiency. This reduction in chlorophyll likely contributed to a lower rate of biomass accumulation, as evidenced by a marked decrease in shoot fresh weight (47.65%) and shoot dry weight (54.73%).

Furthermore, root development was severely compromised by nitrogen omission. There was a noticeable decline in root fresh weight by 65.11% and root dry weight by 66.03%, indicating a stunted root system that could impair water and nutrient uptake. Root length and volume were also reduced significantly, by 29.68% and 61.87%, respectively, compared to the complete fertilization treatment (P1). This suggests that nitrogen is not only essential for above-ground biomass development but also plays a vital role in promoting a robust and extensive root system, which is crucial for the overall growth and stability of the plant (Figure 2).

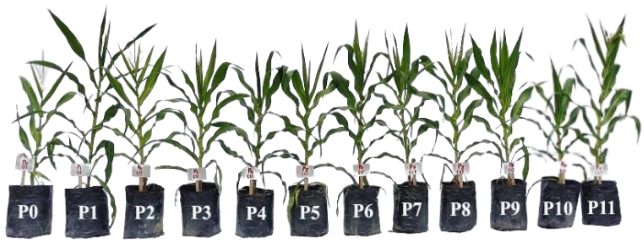

Figure 2. Visual observation of maize plant growth due to nutrient omission techniques fertilization at the age of 2 months after fertilization (MAF)

Interestingly, in contrast to the trend observed with nitrogen, the omission of copper (Cu) (P11) resulted in plants that were taller and had more leaves compared to the complete fertilization treatment. This unexpected outcome might indicate a complex interaction between copper and other nutrients, potentially suggesting that copper may influence hormonal pathways or growth regulation mechanisms differently than other nutrients. Visual assessments at 2 months after fertilization (MAF) showed that plants under the nitrogen omission treatment (P2) were noticeably stunted in height, while those under the copper omission treatment (P11) appeared taller than the fully fertilized plants, hinting at the nuanced role copper plays in maize growth.

In terms of yield characteristics, nutrient omissions significantly influenced key parameters such as cob length, husk weight, cob weight, seed weight, and overall yield per hectare. Nitrogen omission resulted in a considerable reduction in these yield components, with cob length decreasing by 20.11%, husk weight by 49.18%, seed weight by 41.28%, and total yield per hectare by 41.35% compared to the complete fertilization treatment. This emphasizes nitrogen's crucial role in reproductive development and grain filling in maize (see Table 1 and Table 2).

The omission of manganese (Mn) led to the smallest cob weight among all treatments, indicating its specific role in cob development and seed filling processes. Although the data showed that nutrient omissions had negligible effects on flowering and harvesting age, except in the absence of potassium (K), calcium (Ca), magnesium (Mg), and iron (Fe), where flowering was slightly accelerated, these changes were not statistically significant (see Table 3). Moreover, the number of seeds was adversely affected by nutrient omissions, particularly with nitrogen deficiency, resulting in reduced seed count and irregular seed placement within the cob. Visual observations supported these findings, showing smaller cobs with uneven seed distribution in nitrogen-deficient plants.

Correlation analysis provided further insights into how various growth characteristics are interrelated with maize yield. Significant positive correlations were observed between leaf area, total chlorophyll, root length, root volume, and both shoot and root dry weights with overall yield per hectare. Notably, the number of seeds displayed the strongest correlation with yield (0.889**), suggesting it as a critical determinant of productivity. This was followed by cob length (0.747**) and leaf area (0.654**), indicating their importance in predicting maize yield outcomes (see Table 4).

Table 1. The agronomic characteristics of maize plants due to nutrient omission techniques at 1 and 2 months after fertilization (MAF)

Treatments	Plant Height (cm)		Number of Leaves		Leaf Area (cm²)		SPAD Total Chlorophyll	
	1 MAF	2 MAF	1 MAF	2 MAF	1 MAF	2 MAF	1 MAF	2 MAF
P0 (control)	62.15 ns	128.50 ns	4.75 ns	13.90 ns	169.30 ns	245.80 d	39.00 ns	37.10 b
P1 (complete)	74.20 ns	143.80 ns	6.20 ns	15.70 ns	250.40 ns	520.50 a	52.00 ns	54.60 a
P2 (-N)	65.50 ns	133.20 ns	5.10 ns	14.30 ns	197.50 ns	260.70 cd	39.20 ns	38.40 b
P3 (-P)	79.90 ns	134.60 ns	5.80 ns	14.90 ns	245.30 ns	440.20 ab	48.20 ns	50.10 a
P4 (-K)	66.80 ns	151.50 ns	5.50 ns	15.30 ns	203.60 ns	389.90 a-d	48.30 ns	47.50 a
P5 (-Ca)	66.70 ns	137.80 ns	6.10 ns	16.10 ns	221.50 ns	352.30 bcd	44.20 ns	47.60 a
P6 (-Mg)	71.00 ns	146.20 ns	5.10 ns	15.30 ns	199.50 ns	432.10 ab	48.20 ns	46.70 a
P7 (-S)	78.90 ns	142.80 ns	6.10 ns	15.80 ns	246.80 ns	408.40 abc	50.40 ns	46.00 a
P8 (-Mn)	82.00 ns	138.70 ns	5.80 ns	15.50 ns	278.30 ns	410.60 abc	49.50 ns	48.90 a
P9 (-Zn)	81.00 ns	134.80 ns	5.50 ns	14.60 ns	279.90 ns	470.90 ab	49.30 ns	46.20 a
P10 (-Fe)	72.40 ns	143.70 ns	5.10 ns	15.50 ns	247.60 ns	422.70 ab	46.80 ns	46.80 a
P11 (-Cu)	79.30 ns	157.20 ns	5.50 ns	15.90 ns	258.50 ns	445.30 ab	50.20 ns	48.30 a
CV (%)	14.80	9.30	22.50	9.60	27.60	20.50	12.80	9.80

Note: Averages followed by different letters in the same column indicate significant differences based on the DMRT at P<0.05. ns = not significant.

Table 2. The agronomic characteristics of maize plants due to nutrient omission fertilization

Treatments	Fresh Weight (g)		Dry Weight (g)		Roots Length (cm)	Roots Volume (ml)	Root: Shoot Ratio
	Shoots	Roots	Shoots	Roots			
P0 (control)	157.93 d	103.17 b	83.12 b	51.54 d	48.03 c	164.77 d	0.62 ns
P1 (complete)	305.31 a	307.53 a	189.81 a	198.86 a	83.57 a	439.40 a	1.05 ns
P2 (-N)	159.84 d	107.29 b	85.93 b	67.55 cd	58.77 bc	167.53 d	0.79 ns
P3 (-P)	238.49 abc	271.85 a	166.51 ab	155.67 ab	68.57 ab	320.43 a-d	1.03 ns
P4 (-K)	219.56 bcd	257.35 a	101.24 ab	98.31 bcd	64.80 abc	338.33 abc	1.02 ns
P5 (-Ca)	192.75 cd	237.99 a	108.23 ab	99.74 bcd	62.13 bc	179.73 cd	1.36 ns
P6 (-Mg)	254.29 abc	248.38 a	164.60 ab	124.47 a-d	66.60 abc	240.70 bcd	0.77 ns
P7 (-S)	245.57 abc	301.18 a	154.61 ab	174.92 ab	70.57 ab	374.17 ab	1.20 ns
P8 (-Mn)	230.74 a-d	218.20 ab	132.02 ab	106.53 bcd	62.57 bc	264.23 bcd	0.90 ns
P9 (-Zn)	272.18 ab	243.76 a	187.27 a	115.31 a-d	71.60 ab	281.47 a-d	0.60 ns
P10 (-Fe)	228.93 a-d	267.79 a	146.23 ab	143.09 abc	60.83 bc	300.83 a-d	0.98 ns
P11 (-Cu)	272.01 ab	303.13 a	183.06 a	145.37 abc	65.13 abc	312.83 a-d	0.80 ns
CV (%)	17.41	28.67	31.95	36.30	15.45	29.63	26.56

Note: Averages followed by different letters in the same column indicate significant differences based on the DMRT at P<0.05. ns = not significant.

Table 3. The yield characteristics of maize plants under nutrient omission fertilization

Treatments	Flowering Age (days)	Harvesting Age (days)	Cob Stalk Length (cm)	Cob Length (cm)	Husk Weight (g)	Cob Weight (g)	Number of Seeds	Seed Weight (g)	100 Seed Weight (g)
P0 (control)	54.00 ns	94.00 ns	7.12 ns	14.05 d	31.73 abc	32.77 c	242.33 ns	59.90 b	24.65 ns
P1 (complete)	54.00 ns	90.33 ns	10.68 ns	20.29 a	47.34 a	51.21 ab	508.00 ns	155.37 a	37.58 ns
P2 (-N)	53.67 ns	91.00 ns	6.79 ns	16.21 cd	24.06 c	41.16 bc	317.00 ns	91.23 ab	30.94 ns
P3 (-P)	51.33 ns	88.33 ns	9.30 ns	18.18 abc	30.40 abc	49.05 ab	462.33 ns	143.75 a	32.68 ns
P4 (-K)	55.00 ns	95.00 ns	7.26 ns	17.31 abc	38.52 abc	48.52 ab	325.00 ns	108.25 ab	32.29 ns
P5 (-Ca)	55.00 ns	95.33 ns	6.04 ns	16.99 bc	27.37 bc	40.26 bc	421.33 ns	128.76 a	35.65 ns
P6 (-Mg)	54.33 ns	92.33 ns	8.50 ns	19.86 ab	49.30 a	56.44 a	373.00 ns	146.40 a	33.60 ns
P7 (-S)	53.33 ns	91.67 ns	8.28 ns	19.04 abc	44.56 ab	52.78 ab	392.00 ns	127.29 a	35.51 ns
P8 (-Mn)	52.33 ns	93.00 ns	8.02 ns	18.76 abc	30.19 abc	40.11 bc	452.33 ns	148.45 a	33.80 ns
P9 (-Zn)	53.00 ns	92.33 ns	8.72 ns	19.70 ab	47.96 a	47.29 ab	464.33 ns	144.15 a	31.24 ns
P10 (-Fe)	56.00 ns	93.00 ns	7.33 ns	18.78 abc	46.89 a	48.66 ab	393.33 ns	129.95 a	35.27 ns
P11 (-Cu)	53.33 ns	91.00 ns	8.83 ns	19.17 abc	42.30 abc	51.15 ab	480.67 ns	151.99 a	33.81 ns
CV (%)	3.98	3.96	31.21	8.56	25.94	14.42	34.67	26.62	14.29

Note: Averages followed by different letters in the same column indicate significant differences based on the DMRT at P<0.05. ns = not significant.

Table 4. The correlation values of maize growth and yield due to nutrient omission fertilization

	PH	NL	LA	TC	RL	RV	SDW	RDW	FA	HA	CL	NS	1-SW	Y
PH	1	0.378*	0.293	0.133	0.031	0.326	0.265	0.318	0.318	0.196	0.121	-0.064	0.330*	0.048
NL		1	0.492**	0.162	-0.013	0.434**	0.412*	0.449**	0.116	0.070	0.340*	0.144	0.125	0.222
LA			1	0.454**	0.371*	0.630**	0.738**	0.561**	-0.175	-0.323	0.773**	0.592**	0.121	0.654**
TC				1	0.446**	0.304	0.139	0.310	-0.047	0.022	0.398*	0.149	0.501**	0.394*
RL					1	0.262	0.197	0.183	-0.133	-0.060	0.447**	0.409*	0.369*	0.582**
RV						1	0.523**	0.772**	-0.226	-0.358*	0.518**	0.435**	0.193	0.416*
SDW							1	0.589**	-0.130	-0.370*	0.677**	0.471**	0.017	0.466**
RDW								1	-0.192	-0.298	0.431**	0.364*	0.396*	0.405*
FA									1	0.679**	-0.159	-0.506**	0.220	-0.451**
HA										1	-0.381*	-0.409*	0.175	-0.305
CL											1	0.634**	0.092	0.747**
NS												1	-0.039	0.889**
1-SW													1	0.156
Y														1

Note: * and ** indicate that the correlation is significant at the 0.05 and 0.01 levels (2-tailed), respectively. n = 36 samples. PH = Plant height; NL = Number of leaves; LA = Leaf area; TC = Total chlorophyll; RL = Roots length; RV = Roots volume; SDW = Shoots dry weight; RDW = Roots dry weight; FA = Flowering age; HA = Harvesting age; CL = Cob length; NS = Number of seeds; 1-SW = 100 seed weight; Y = Yield per hectare.

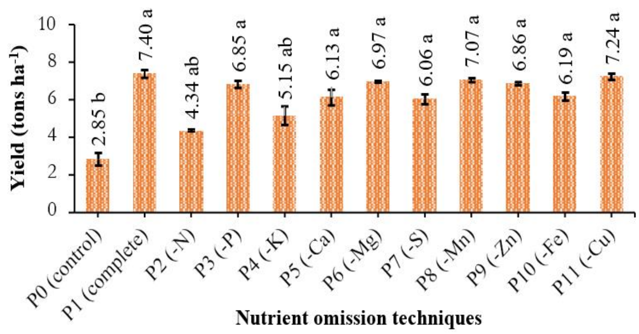

Figure 3. Yield ha^{-1} of maize plant due to nutrient omission techniques fertilization

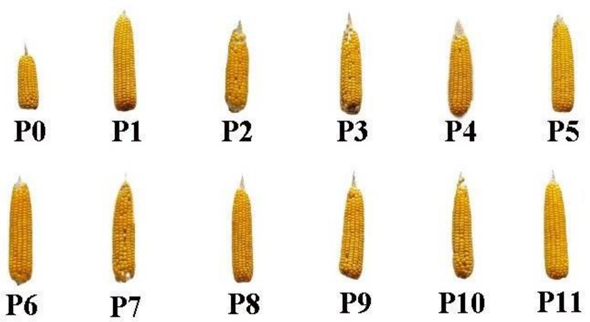

Figure 4. Visual observation of maize cobs due to nutrient omission techniques fertilization

These findings show the paramount importance of nitrogen for both vegetative and reproductive growth in maize, influencing a wide range of parameters from leaf area to yield (Figure 3). The results also underscore the complex interactions between various nutrients, such as the unexpected growth promotion in copper-omitted plants (Figure 4). Overall, a balanced nutrient supply is essential for optimizing maize growth and achieving high yield potential, with particular emphasis on nitrogen's multifaceted role in plant development.

4. DISCUSSION

The nutrient omission techniques used in this study had a pronounced impact on various agronomic characteristics of maize plants, particularly in treatments where nitrogen was omitted. Nitrogen deficiency was observed to significantly reduce leaf area, total chlorophyll content, biomass accumulation, root length, and root volume. The reductions ranged between 29.44% and 66.03% when compared to the complete fertilization treatment. This underscores the critical role of nitrogen in the physiological and biochemical processes that underpin maize growth. Nitrogen is a key component of chlorophyll molecules and amino acids, making it essential for photosynthesis and protein synthesis. The observed decline in leaf area and chlorophyll content indicates a compromised photosynthetic capacity, leading to reduced biomass production.

Furthermore, the reductions in root length and volume due to nitrogen deficiency suggest an impaired nutrient and water uptake system, further affecting the plant's overall growth. Roots play a crucial role in absorbing water and nutrients from the soil, and their development is often dependent on adequate nitrogen availability. The study found a strong positive correlation between leaf area, root volume, and both shoot and root dry weights (correlation values of 0.738** and 0.561** for shoot dry weight; 0.523** and 0.772** for root dry weight), indicating that nitrogen deficiency disrupts the plant's ability to establish a robust root system. This disruption not only limits nutrient uptake but also compromises the plant's ability to sustain growth and develop a strong shoot system.

These findings align with previous research, such as Zhao et al. [22], who reported that nitrogen deficiency significantly inhibits leaf area expansion, chlorophyll content, and photosynthetic rate, thereby leading to lower biomass accumulation. Moreover, Fan et al. [23] demonstrated that under nitrogen deficiency, the specific leaf area and nitrogen content in maize shoots decreased markedly during the vegetative stage, resulting in stunted growth. The inhibition of root growth further supports findings by Gao et al. [24], who indicated that nitrogen deficiency leads to a reduction in the root-to-shoot ratio and lateral root density, hampering the plant's overall nutrient absorption efficiency.

When examining the effect on yield-related characteristics, nitrogen omission resulted in a marked reduction in cob length, husk weight, cob weight, seed weight, and overall yield per hectare. The reductions ranged from 20.11% to 49.18%, emphasizing nitrogen's role in reproductive development and grain filling. The limitations in yield were closely linked to the earlier stages of growth, where reduced leaf area and chlorophyll content impeded photosynthetic efficiency and thus limited the resources available for reproductive development. This was evident from the positive correlations observed between yield per hectare and various growth characteristics, such as leaf area (0.654**), total chlorophyll (0.394*), root length (0.582**), root volume (0.416*), and dry weights of shoots and roots (0.466** and 0.405*, respectively). These correlations highlight how growth stage characteristics directly impact final yield outcomes.

This outcome aligns with studies such as Muhammad et al. [25] and Bojtor et al. [26], which also reported that nitrogen omission leads to significant reductions in leaf area, biomass, chlorophyll content, and seed weight. The limitation in nitrogen availability restricts photosynthate production and translocation, resulting in fewer resources being allocated to cob and seed development. Consequently, maize plants with nitrogen deficiency produced shorter cobs with fewer and smaller seeds. Additionally, Afrida et al. [27] found that the absence of nitrogen fertilization caused a significant inhibition in seed development, further affirming nitrogen's pivotal role in supporting both vegetative and reproductive growth phases.

Interestingly, the impact of other nutrient omissions such as potassium (K), sulfur (S), calcium (Ca), and micronutrients like zinc (Zn) and manganese (Mn) were also notable but less severe compared to nitrogen. Potassium omission was the second most limiting factor after nitrogen, indicating its critical role in enzyme activation, osmoregulation, and photosynthate transport. Without adequate potassium, the translocation of sugars from leaves to developing cobs is hindered, impacting cob size and seed fill. The study's sequence of nutrient limitation (-N < -K < -S < -Ca < -Fe < -P < -Zn < -Mg < -Mn < -Cu) offers a comprehensive understanding of the relative importance of these nutrients in maize production, suggesting that while nitrogen is the most crucial, other nutrients also play essential roles in optimizing yield.

Aliyu et al. [28] corroborate these findings by showing that the absence of potassium and nitrogen significantly lowers maize yield per hectare. They highlighted the intricate balance required among various nutrients to achieve optimal growth and productivity, suggesting that the absence of specific nutrients like nitrogen and potassium leads to cascading effects on other nutrient interactions and availability, ultimately affecting yield.

The overall conclusion from this study and the supporting literature emphasizes the need for a balanced nutrient management strategy in maize cultivation. Nitrogen, while being the most critical for growth and yield, interacts with other nutrients, and its deficiency leads to a compounding effect on maize productivity. Therefore, the management of nitrogen along with other essential macro and micronutrients is paramount for achieving optimal growth and maximizing yield in maize production. These insights are crucial for informing fertilizer application strategies, ensuring sustainable and efficient nutrient use in maize farming systems.

5. CONCLUSION

The research reveals that nutrient omission techniques significantly impacted maize growth parameters more severely than yield characteristics, with reductions in growth metrics ranging from 29.44% to 66.03%, particularly in treatments lacking nitrogen. The study confirms nitrogen's pivotal role in maize development, as its omission consistently resulted in the greatest inhibition of essential agronomic traits, including leaf area, total chlorophyll content, root length, root volume, and both shoot and root biomass. These growth attributes were found to be highly correlated with yield outcomes, indicating their direct influence on maize productivity. Specifically, leaf area and root volume were among the strongest contributors to enhanced yield, with correlation values of 0.654** and 0.582**, respectively.

The research highlights the hierarchical importance of various macro- and micronutrients in sustaining maize yield, identifying nitrogen and potassium as the most critical limiting factors. Nitrogen, as a vital component of chlorophyll and proteins, plays a foundational role in photosynthesis and biomass accumulation, while potassium supports key physiological processes such as enzyme activation, water regulation, and sugar transport. The nutrient omission sequence established in this study (-N < -K < -S < -Ca < -Fe < -P < -Zn < -Mg < -Mn < -Cu) provides critical insights for nutrient management strategies, underscoring that the absence of nitrogen and potassium not only hampers growth but also significantly reduces yield by limiting cob and seed development.

Moreover, the findings emphasize the complex interaction between macro- and micronutrients in promoting optimal maize productivity. While nitrogen and potassium were the most limiting, sulfur and calcium also played notable roles in plant development. The reduced presence of sulfur, which is essential for amino acid synthesis, and calcium, important for cell wall integrity, contributed to diminished plant growth and yield, although to a lesser extent than nitrogen and potassium.

The study suggests that sustainable maize production requires a holistic nutrient management approach, balancing the application of both macro- and micronutrients. Nitrogen and potassium should be prioritized in fertilization regimes due to their significant influence on both vegetative and reproductive growth stages. However, secondary nutrients such as sulfur and calcium should not be overlooked, as their combined effects with nitrogen and potassium are essential for achieving maximum maize yield potential. These findings provide a strong basis for optimizing fertilizer use in maize cultivation, supporting the need for targeted nutrient interventions that align with specific growth phases and soil nutrient profiles.

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