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Root Plasticity of Selected Corn (*Zea mays* L.) Varieties Grown for Food and Forage in Response to Fertigroe®-N and Urea

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Root plasticity, the capacity of a corn root system to modify its growth and development in response to varying environmental conditions, is a crucial adaptability trait for optimizing water and nutrient uptake, especially in challenging environments. Understanding root plasticity provides insights into the pattern basis of crop adaptation, contributing to the development of improved corn varieties and agricultural practices that optimize the production of both ear shoots and forage. This study assessed root traits and other morphological-physiological responses of three corn varieties (NK8840, IPB Var 6, and Pearl Sweet) grown for food (ear shoots) and forage (baby corn fodder) to FertiGroe®-N and urea fertilizers. The experiment used a two-factor randomized block design with three replications, conducted from August 2021 to February 2022 in Tiaong, Quezon, Philippines using PVC tubes filled with 20 kg of soil. Results revealed that FertiGroe®-N significantly increased root weight, length, volume, and diameter compared to urea, particularly at two to three days after silking (R_1) stage. This enhanced root growth translated into improved shoot growth, Soil and Plant Analysis Development (SPAD) chlorophyll values, total dry matter (TDM), and both ear shoot and forage yield. Root length (0.91) and weight (0.89) showed strong positive correlations with ear shoot and forage yield, respectively. Similarly, plant height (0.98) and root weight (0.97) exhibited high correlations with their respective yields, while TDM demonstrated significant correlations with both ear shoot (0.99) and forage yield (0.97). These findings imply that applying FertiGroe®-N at a rate of 160 kg N effectively enhances root traits and consequently improves ear shoot and forage yields.

Keywords: corn, root plasticity, nanofertilizer, nutrient use efficiency

INTRODUCTION

Root phenotype plasticity allows plants to adapt to biotic and abiotic constraints that limit the crop to productivity (Schneider and Lynch 2020). It is a trait that can be influenced by genetics (Schneider et al. 2020) and sensitivity to external stimuli (Huang and Zhang 2020). Root phenotype plasticity is not only an adaptive response but also a pattern of change or development. Research on root architecture plasticity may help during carbon assimilation with increased capacity for soil sources acquisition (Harter et al. 2015).

Nitrogen (N), a vital macronutrient, is often limiting in agricultural soils. Plants have developed mechanisms to detect and respond to nitrogen availability, modifying their root structure and physiological processes to optimize nitrogen absorption. Sun et al. (2020) reported that auxin transport from the shoot to the root rises in response to a low shoot nitrogen status signal. Then, nitric oxide is produced in the root tip promoting strigolactones, which speeds up cell division in roots. This will increase root elongation, thus increasing root weight. A study by Chen et al. (2020) found that moderate to high nitrogen fertilization rates (240 kg ha^{-1}) had a beneficial impact on root length, root surface area, and root biomass across most soil layers. Notably, the total root growth and biomass increased by more than 36% when compared to no nitrogen application. However, Lopez et al. (2023) reported that root length decreased by 9% under N deficiency. In addition, root weight density (RWD) of corn in the 0–100 cm soil layer increased rapidly after the V_6 stage and reached the maximum at the R_2 stage, followed by a sharp decline until the R_6 stage. Grossman and Rice (2012) demonstrated that barley had a larger root diameter in pots with high fertilizer levels, while Liu et al. (2013) found that nitrate stimulated lateral root growth in corn.

Nanofertilizers represent a cutting-edge approach to nutrient delivery in agriculture. These fertilizers utilize nanoparticles to facilitate more efficient nutrient uptake, reduce nutrient leaching, promote gradual and sustained release over time (Liu and Lal 2015). Moreover, it has the potential to improve yield and efficiency due to its properties such as greater absorbance and high reactivity (Yang et al. 2019). Consequently, nanofertilizers can significantly enhance plant growth and productivity by addressing nutrient deficiencies more effectively than traditional fertilizers.

FertiGroe®-N is a nanofertilizer developed at the University of the Philippines Los Baños, Laguna, Philippines. Despite its innovative formulation, there has been limited research on its standard application, effects, and benefits across various crops. Previous studies focusing on corn have primarily examined grain yield and biomass; however, investigations into its impact on corn grown specifically for ear shoots and forage is limited. This study investigated the responses of three corn varieties grown for dual purposes (food and forage) when applied with urea and FertiGroe®-N grown in PVC. By evaluating root traits, shoot growth, leaf area index, chlorophyll content, and total biomass, this research aimed to examine the nitrogen use efficiency mechanisms that significantly influence the growth and productivity of corn intended for food and forage. Understanding these responses is crucial for optimizing fertilizer use and enhancing the sustainability of corn production.

MATERIALS AND METHODS

Experimental Design and Treatments

The experiment was conducted from November 2021 to February 2022 using a Randomized Complete Block Design (RCBD) with two factors. Factor A was allocated to the nitrogen source (FertiGroe®-N, urea, and no nitrogen applied) and factor B was allocated to three corn varieties (Syngenta hybrid NK8840 EZ Refuge, IPB Var 6, and UPLB Pearl Sweet or PSB CN-93-49). Plants were grown in polyvinyl chloride (PVC) tubes that were filled with 20 kg of soil from the Quezon Agricultural Station (QAES). Tubes measuring 20 cm wide and 100 cm long were used and were spaced 20 cm apart. Soils were sieved before being placed into the PVC tubes. Three plant samples of each treatment per replicate were used to study plant growth, root morphology, and plant biomass. The recommended rate of 160-90-60 (NPK) was used based on the recommended rate after soil analysis. Split-nitrogen application was applied at basal and 25 d after planting (DAP), while the recommended full amount of phosphorous and potassium was applied at basal. Plants were watered every other day at initial 1st wk establishment until field water capacity. Thereafter, the whole corn growth until ear shoot stage was rainfed. The initial stage of data collection was at 30 DAP, and successive data collection was gathered at VT and R_1. The number of days it took to reach the physiological VT and R_1 phases varied depending on the varieties. Table 1 shows the estimated physiological phases of the different varieties tested (A.K. Beltran, personal communication, January 2021; L. Pabro, personal communication, January 2021).

Table 1. Characteristics of IPB Var 6, NK8840, and UPLB Pearl Sweet (PSB CN-93-49).

Characteristics	NSIC Cn 2008-224 (IPB Var 6)	NK8840	UPLB Pearl Sweet or PSB CN-93-49
Days to Tassel	44–45	44–45	38–39
Days to Silking	45–46	46–47	40–42
Maturity (days)			
Dry Season:	105	105	72
Wet Season:	101	100.7	No Data

1. ***Plant height (cm).*** It was measured from the base of the corn plant to the tip of the longest leaf during the vegetative stage. At the reproductive stage, the measurement was taken from the base of the plant to at collar of the 1st base of the tassel.

2. ***Leaf area (cm^2)***. The youngest fully expanded leaf per plant was used. Leaf area was determined using the formula of Castleberry et al. (1978) as cited by Balisi (1995).

LA = leaf length (cm) × maximum leaf width (cm) × factor (0.75)

3. ***Stem diameter (cm)***. The thickest part of the stalk at the last node near the roots was measured using a Vernier caliper.

4. ***Root characters.*** Root volume, root dry weight, root base diameters, and longest root length were obtained in experiments. Soils were removed from the roots by soaking and rinsing them with running water. After removing the excess water, the following root analysis was conducted.

a. *Root dry weight (g)* – Root fresh weight was measured after destructive sampling. Then, each root was oven-dried at 50°C for 5 d. Dry weight was weighed to obtain the root dry weight.

b. *Longest root length (cm)*. The primary root length was obtained using a ruler.

c. *Root base diameter (mm).* The root base diameter was measured using a caliper (inches).

d. *Root volume (mL).* The volume of roots at ear shoot stage was obtained using the displacement method. The initial level of water in the beaker was 500 mL. Then, each root was placed in the beaker and the final level of water was obtained. The initial volume of water was subtracted from the final volume of water to get the root volume.

5. ***Above-ground biomass partitioning.*** Samples were collected and partitioned into leaves, stem, roots, tassel, and ear shoot. This was followed by weighing the fresh weight of the different plant organs, then the total fresh weight was obtained. After weighing, samples were chopped and oven-dried at 50°C for five consecutive days. After obtaining the dry matter weight, subsamples were obtained for nitrogen analysis. In computing the total biomass, only the upper biomass was included. The dry matter was also used in the following formula and analysis.

a. *Dry matter of portioned plant parts* = Fresh weight - (Fresh Wt. x MC)

b. *Yield (g plant $^{-1}$).* Ear shoot and forage yield were collected at R_1 growth stage. Forage yield includes leaves and stem.

Data Analysis

Data analysis was conducted using ANOVA in STAR 2.0.1, a statistical software developed by the International Rice Research Institute (IRRI). Significant differences between treatment means were compared using the Least Significant Difference (LSD) test. Correlation of morpho-physiological responses and yield was analyzed using the STAR 2.0.1 package.

RESULTS AND DISCUSSION

Soil Analysis

Results of the initial analysis for soil pH, organic matter, and levels of N are summarized in Table 2. The initial chemical characteristics of the field classify it as Guadalupe clay loam with a medium pH of 5.4 and 3.36% organic matter. The total nitrogen is found to be at a medium level of 0.17%. Clay loam soils have significant numbers of small soil particles with a large surface area indicating better nutrient and water holding capacity. This soil characteristic is beneficial to corn production, particularly to those areas that are highly dependent on rain for irrigation. Table 2 shows the soil sample's chemical properties after the experiment. Results showed that the mean pH and nitrogen levels did not differ significantly. However, there were significant differences in organic matter among the different N sources. Treatments applied with FertiGroe®-N showed the least reduction in the soil's organic matter compared with treatments applied with urea and No N treatments. This could be attributed to the less detrimental impact of FertiGroe®-N on microbial organisms compared to urea, as previously reported by Basay et al. (2021). Furthermore, Pide et al. (2022) demonstrated that FertiGroe®-N can stimulate the growth of nitrogen-fixing bacterial communities such as Acidimicrobiia, Chloroflexia, and Gemmatimonadetes, which can subsequently enhance soil organic matter decomposition (Olanrewaju et al. 2017).

Table 2. Chemical properties of soil used for the experiment before and after planting.

	Treatments	Soil Property		
Field samples before planting		Soil pH	Organic Matter (%)	Nitrogen (%)
		5.40	3.36	0.17
Field samples after planting	T1- N- FertiGroe®-N	5.07	2.71 a	0.1267
	T2 - Urea	5.00	1.30 b	0.1067
	T3 - No nitrogen	4.97	1.13 b	0.1367
	p-value	0.60ns	0.0007**	0.70ns

**highly significant indicates $p < 0.01$, * significant indicates $p < 0.05$; ns, does not differ significantly $p > 0.05$ at 0.05 probability. V_6 (6th visible collar leaf), VT (tasseling stage), and R_1 (2–3 cm silking stage)

Climatic Data

Fig. 1 presents the weather data from soil preparation (August 2021) and time of planting (September 2021) until harvesting time (October-November 2021) of ear shoot (DA-Region IV-A-Calabarzon-Sariaya 2021). Temperature and rainfall are two important weather conditions that can affect corn growth. The optimum temperature for seedling emergence, tasseling, and ear shoot are 27°C, 25°C, and 30°C, respectively (Hulmani et al. 2022). During the ear shoot growing season, the average daily air temperature was 24°C, but no detrimental effect on the crop was observed. The total precipitation was 71.2 mm (September 2021) and 72.9 mm (October 2021). Generally, the prevailing weather in the duration of the trial was within the adaptability of the corn and the crop trial was successfully harvested and concluded.

Plant Growth Traits

Effects of N sources, genotypes, and their interactions on plant height, stem width, and leaf area from V_6 to R_1 were measured ($p < 0.1$). Significant N source and genotype effects were also consistently observed in all traits ($p < 0.1$). Nitrogen source and genotype interaction were significant only for plant height, longest root length, and root diameter across sampling times ($p < 0.1$).

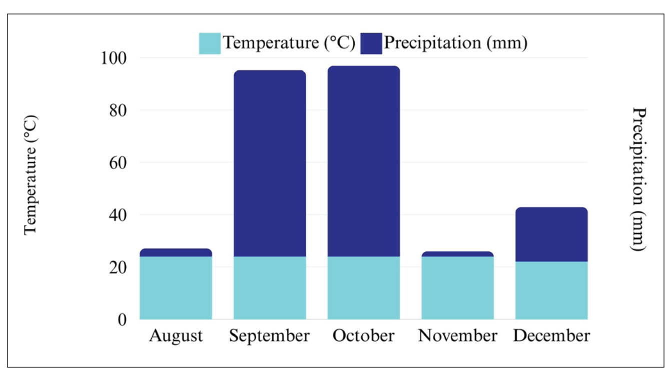


Fig. 1. Average temperature and rainfall from August to December 2021.

Plant height

Fig. 2 presents the plant heights of three varieties fertilized with different N sources at V_6, VT, and R_1. Pearl Sweet showed a consistently shorter height compared with all varieties across all growth stages fertilized with either FertiGroe®-N and urea.

Varieties NK8840 and IPB Var 6 had statistically similar plant heights at all growth stages, reaching a maximum height of 200 cm at R_1. The consistent height differences among varieties suggest strong genetic control over plant height. This is supported by previous research (Yu et al. 2021) indicating that genetic factors influence various traits associated with plant height, including internode length.

Expectedly, the plant heights of all varieties were shorter without fertilizer at all growth stages. While genetics play a crucial role, environmental conditions and management practices, such as N fertilization, can also influence plant height. The positive response of plant height to N fertilization in all varieties emphasizes the need for adequate N supply to support optimal plant growth.

Plant height is an important trait related to N uptake and assimilation that is associated with other traits such as leaf area, biomass, and yield. As reported by Zhou et al. (2018), plant height, along with related traits such as ear height and internode number, are critical factors influencing biomass, planting density, and, ultimately, grain yield.

Chlorophyll

Chlorophyll content, a key component of photosynthetic pigments and enzymes (Khangura et al. 2020), is often used as an indicator of plant nitrogen status. This parameter is closely linked to photosynthetic efficiency and can be a valuable tool for nitrogen management (Mu and Chen 2022). Variety, N source, and Variety x N source interaction had significant effects in all growth stages.

Variety NK8840 EZ Refuge generally had the highest chlorophyll levels across all treatments at all growth stages. This variety appears to be able to maintain higher chlorophyll levels compared with IPB Var 6 at V_6 and with Pearl Sweet at all growth stages across N sources (Fig. 2). This implies that application of FertiGroe®-N and urea increased chlorophyll levels of corn compared to control. This increased assimilation of photosynthates led to a rise in corn leaf area (LA) and other plant growth features. A larger leaf area allows for increased light interception, which, in turn, drives photosynthesis and the accumulation of biomass, including leaf tissue. A higher leaf area index (LAI) is indicative of a plant with a greater total leaf surface area, which directly contributes to its overall leaf weight.

Plants have already absorbed around half of the applied N by the V_8 –VT growth stage (Butzen 2011). Despite this, their nitrogen demand extends into the reproductive phase; approximately one-third of the total nitrogen requirement must still be taken up during the ear-fill period (Ritchie et al. 2005). This study shows that FertiGroe®-N's proper timing and slow-release attributes were effective in enhancing and maintaining chlorophyll content, which is important in photosynthesis and plant growth.

Biomass Partitioning

Consistent significant effects of N source and genotypes were found on biomass partitioning to the leaves, stem, roots, and ear shoot ($p < 0.01$). However, only the genotype significantly influences the biomass partitioning in the tassel at VT and R_1, while the interaction effect was consistent on the stem and the leaves at VT and R_1, except at V_6. Moreover, interaction effect on root biomass was significant in all stages ($p < 0.01$).

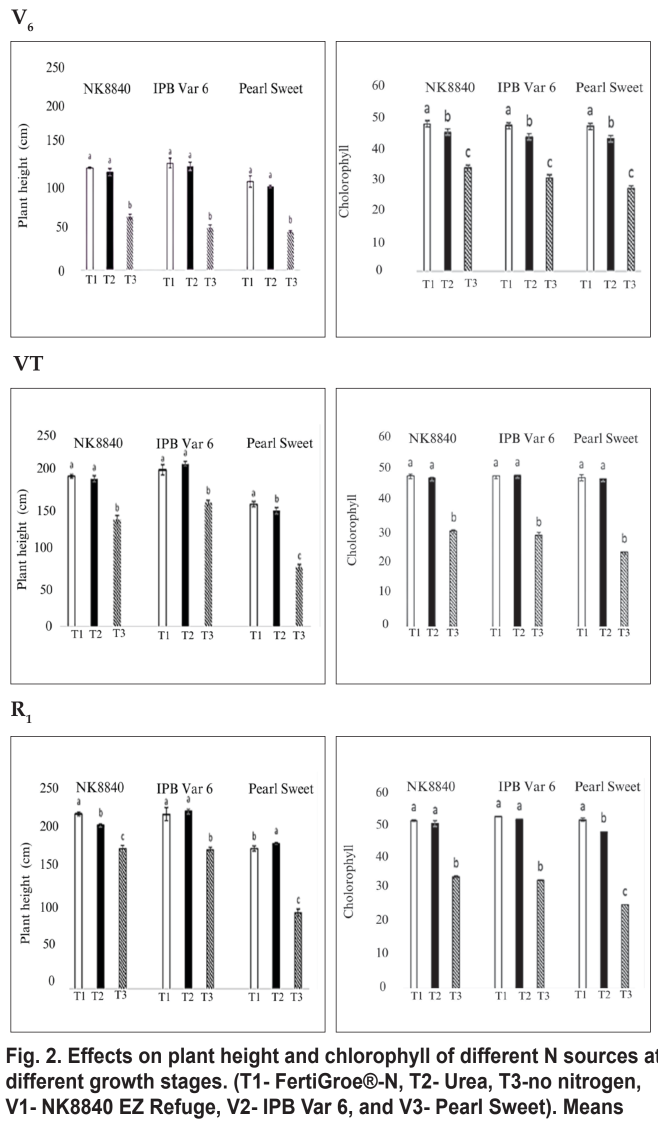
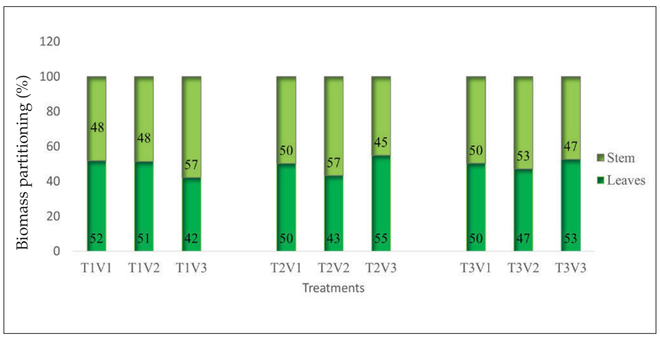


Fig. 2. Effects on plant height and chlorophyll of different N sources at different growth stages. (T1- FertiGroe®-N, T2- Urea, T3-no nitrogen, V1- NK8840 EZ Refuge, V2- IPB Var 6, and V3- Pearl Sweet). Means within columns with the same letter(s) are not significantly different at 0.05 level of significance using LSD. Vertical bars represent standard error of means (*n* = 3).

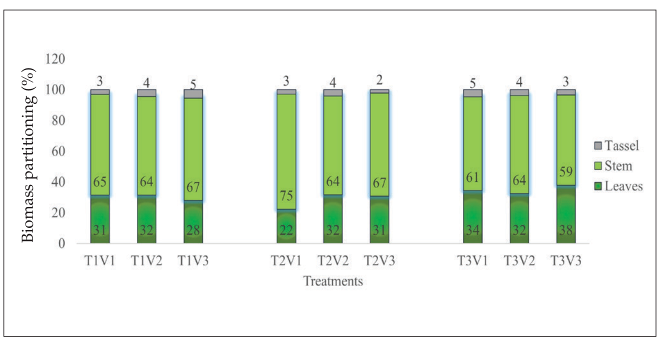
Biomass partitioning in corn helps in understanding the distribution and utilization of nitrogen and estimate the nutrient distribution between vegetative and reproductive components. The optimal partitioning theory suggests that plants distribute biomass between the leaves, stems, and roots to maximize the acquisition of the most limiting resources (Yang et al. 2024).

Corn dry matter partitioning to the leaves, stem, tassel, and ear shoot is presented in Fig. 3. Partitioning to the leaves, stem, tassel, and ear corn significantly differed by N source at V_6, VT, and R_1. Fertilized plants had higher biomass partitioned to organs compared with the control. In this study, more biomass was found at the leaves and the stem components in all treatments at V_6 (Fig. 3a).

(a) V_6



(b) VT



(c) R_1

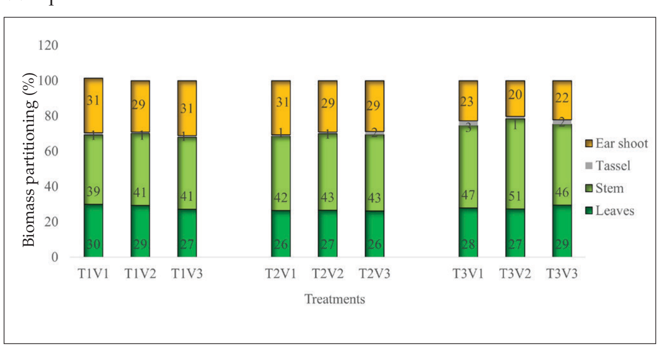


Fig. 3. Biomass partitioning of corn at different stages: (a) V_6, (b) VT, and (c) VT-R_1. T1-FertiGroe®-N, T2- Urea, T3-No nitrogen; V1- NK8840 EZ Refuge, V2- IPB Var 6, and V3- Pearl Sweet); V6 (6th visible collar leaf), VT (tasseling stage), and R_1 (after 2 d silk emergence). Vertical bars represent standard error of means (n = 3).

A shift in more biomass allocation to the stem compared with other parts was observed at VT (Fig. 3b) and continued at R_1 in all treatments. At V_6, with the increasing leaf area and number of leaves, the plant manufactures and supplies food to other growing organs.

Allocation of more assimilates in the stem in VT shows the sink's capacity to draw more assimilates as the plant aged. During VT, the stem grew as the leaves emerged, increasing photosynthesis. At VT and R_1, biomass partitioning to leaves was reduced due to leaf senescence and fall, reducing leaf biomass. Furthermore, the dry matter portioned to the ear shoot started to increase, while the dry matter partitioning to the leaves and stem decreased as plants approached the reproductive stage. At R_1, stem biomass was re-allocated to the growing ear shoot and the leaf biomass was reduced in all varieties across all treatments, apparently due to leaf senescence and fall (Fig. 3c). The reports of Taiz et al. (2015) support this study's observation that shifts in dry matter pattern occurred due to plant aging and sink capacity.

Total Biomass

Total dry matter (biomass dry weight) is the most important parameter for corn grown for forage. Total biomass at the VT and R_1 stages was significantly influenced by the interaction between N-source and genotype ($p < 0.1$). Variety and N source influenced the biomass in all growth stages (Fig. 4). Generally, NK8840 and IPB Var 6 produced higher biomass (g) per plant across N sources and growth stages compared with Pearl Sweet.

Expectedly, fertilized treatments across varieties and growth stages also produced higher biomass. Plants treated with FertiGroe®-N produced comparable biomass in all varieties in V_6 and VT and higher biomass at harvest (R_1). This implies that FertiGroe®-N provided the necessary N to increase growth and, eventually, total plant biomass. The low N supply in control resulted in slow and low growth rate, consequently resulting in low biomass. Expectedly, the biomass of N-treated plants were superior over the control plants in all stages and varieties.

Ear Shoot and Forage Yield

Significant interaction effect of N source and genotypes was only found on forage but not on ear shoot yield in all growth stages. Table 3 presents the mean effect of N source and varieties on ear shoot yield. Generally, ear shoot and forage yield increased with N fertilization. Significantly highest ear shoot (Table 3a) and forage yield (Fig. 5) were found in plants applied with FertiGroe®-N.

The higher ear shoots and forage yields with FertiGroe®-N than other treatments can be associated with the crop's nutrient content, better nutrient mobilization, and timely assimilate allocation provided by FertiGroe®-N. This result is in line

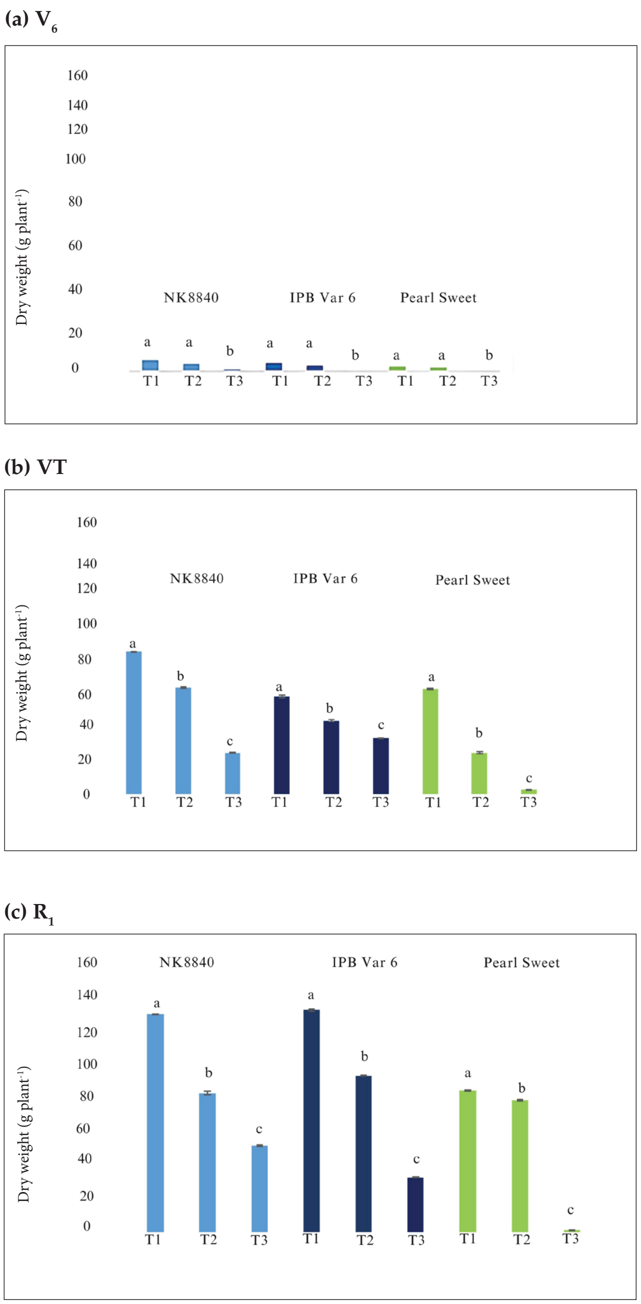


Fig. 4. Dry matter weight of corn at different stages: (a) V_6, (b) VT, and (c) VT-R1. T1- Fertigroe ® -N, T2- Urea, T3-no nitrogen; V1- NK8840, V2- IPB Var 6, V3- Pearl Sweet. V_6 (6th visible collar leaf), VT (tasseling stage), and R1 (2 d after silking). Vertical bars represent standard error of means (*n* = 3).

Table 3a. Effect of N source on ear shoot yield.

N Source	Ear Shoot Yield (g plant $^{-1}$/day)
T1 - FertiGroe®-N	33.63 a
T2 - Urea	25.31 b
T3 - No nitrogen	6.02 c

Means within a column with the same letter (s) are not significantly different at 0.05 level of significance using LSD.

with the study of Ramirez Builes et al. (2011) who found that nutrient partitioning and utilization can control productivity. High ear shoot and forage yield imply that FertiGroe®-N can be a potential N source. Furthermore, this study shows the potential of FertiGroe®-N in improving ear shoot and forage yield which supports recent reports and reviews on the effectivity of nanofertilizers in improving the yield of different crops such as wheat (Sheoran et al. 2021), rice (Dore et al. 2018), tomato (Panda et al. 2020), and corn (Kumaraswamy et al. 2021). Genetic traits of plants can influence yield and total dry matter as reported by Galizia et al. (2020). Yang et al. (2023) also reported that nanofertilizer application can stimulate the expression of genes involved in nitrogen transport and metabolism, leading to increased nitrogen accumulation and improved yield.

As shown in Table 3b, NK8840 EZ Refuge and IPB Var 6 demonstrated significantly higher ear shoots and forage yields than Pearl Sweet, highlighting the influence of genotype on these traits. The higher yields of NK8840 EZ Refuge and IPB Var 6 can be attributed to their photosynthetic efficiency, water use efficiency, and nutrient uptake capabilities. The structure and arrangement of the plant, such as stem height, leaf area, and tassel development, can influence light interception, photosynthesis, and reproductive growth. Furthermore, ear traits exhibited heritability values greater than 0.5, showing the significant role of genetics in corn ear traits (Wang et al. 2023).

Harvest Index

The harvest index (HI) reflects the efficiency of assimilate allocation into marketable plant output. Influences on harvest index of N source, genotypes, and their interactions were significant ($p < 0.01$). Fig. 6 shows that FertiGroe®-N and urea had the highest % HI compared to control among varieties, except for IPB Var 6 which had statistically higher HI with urea. The HI obtained was relatively similar to the HI (2.46) reported by Das and Kumari (2020), indicating that the higher HI in N-treated plants can be attributed to the plasticity of plants to utilize assimilates into ear shoot yield to produce economic yield.

Table 3b. Effect of varieties on ear shoot yield.

Variety	Ear Shoot Yield (g plant $^{-1}$/day)
V1 - NK8840 EZ Refuge	28.06 a
V2 - IPB Var 6	21.64 ab
V3 - Pearl Sweet	15.27 b

Means within a column with the same letter (s) are not significantly different at 0.05 level of significance using LSD.

Root traits

Nitrogen source, variety, and their interaction significantly affected root weight, root volume, root length, root diameter, and root shoot ratio in all growth stages ($p < 0.1$). There was a significant interaction between N source and variety on root base diameter, and root volume across varieties and in all stages ($p < 0.1$)

Root weight

Fig. 7 summarizes the trend of the different root traits at different sampling times from V_6 to R_1. Higher values for all root traits were observed in the N-fertilized plants compared with the control at all sampling times. There was a significant N source and

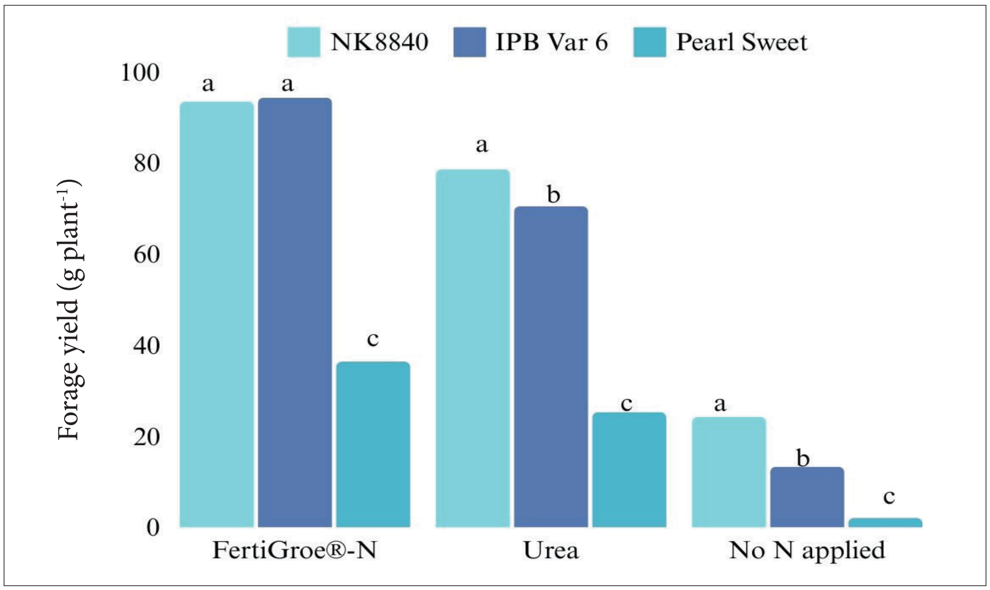


Fig. 5. Forage yield. T1-FertiGroe®-N , T2- Urea, T3-no nitrogen, V1- NK8840 EZ Refuge, V2- IPB Var 6, and V3- Pearl Sweet, R_1 (after 2 cm silk emergence). Vertical bars represent standard error of means (*n* = 3).

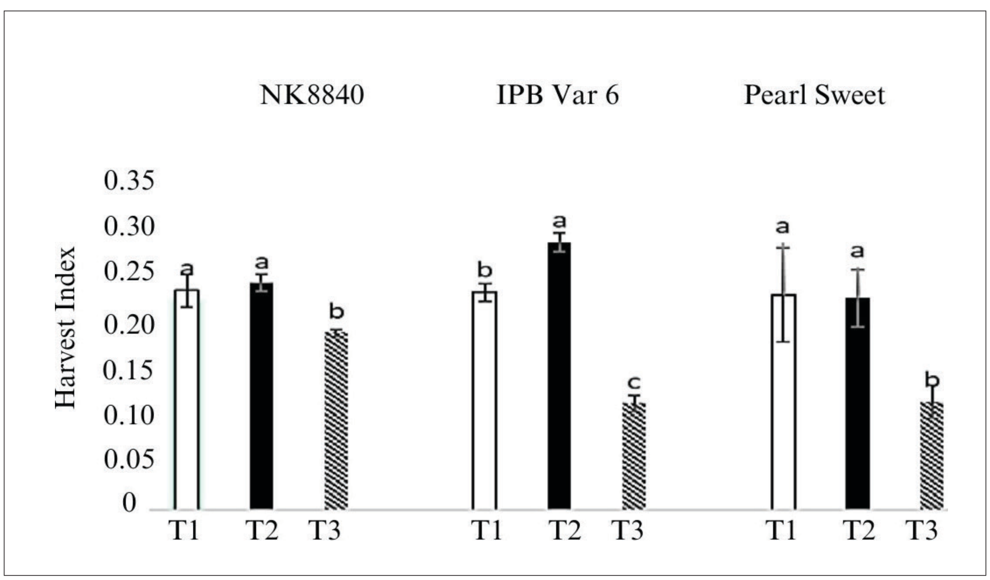


Fig. 6. Harvest index of corn. (T1-FertiGroe®-N, T2- Urea, T3-no nitrogen, V1- NK8840 EZ Refuge, V2- IPB Var 6, and V3- Pearl Sweet). Vertical bars represent standard error of means (*n* = 3).

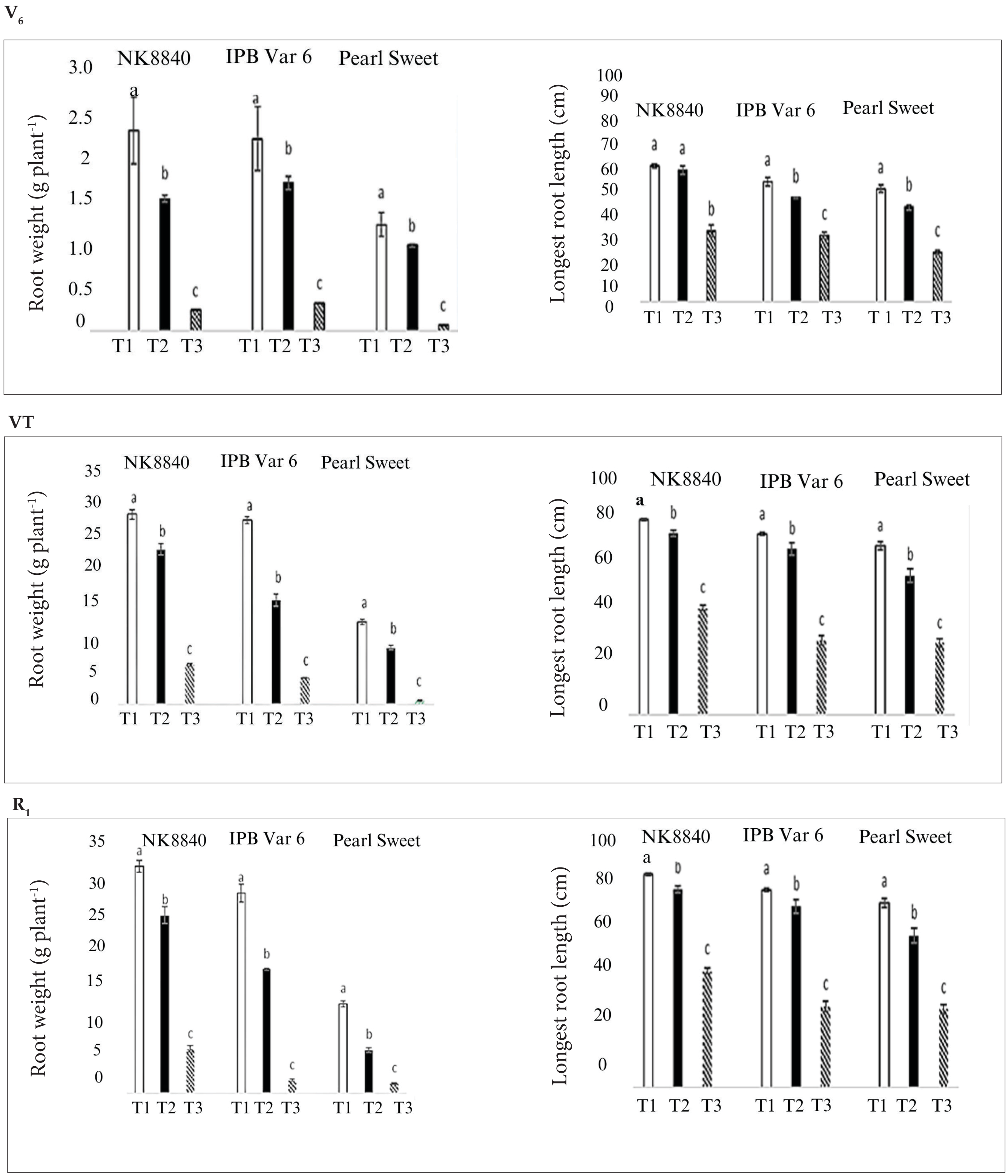


Fig. 7. Effects on (a) root weight and (b) root length of different N sources at different growth stages. T1- FertiGroe®-N, T2- Urea, T3-no nitrogen, V1- NK8840 EZ Refuge, V2- IPB Var 6, and V3- Pearl Sweet. Means within columns with the same letter(s) are not significantly different at 0.05 level of significance using LSD.

variety interaction in root weight and longest root length at all stages. The average root weight of NK8840 EZ Refuge and IPB Var 6 was comparable and the highest among both fertilized treatments and the control at V_6, as shown in Fig. 7a.

The root weights of hybrid NK8840 EZ Refuge and IPB Var 6 were consistently higher than Pearl Sweet across fertilizer treatments at all growth stages. Expectedly, N-fertilized treatments also had higher root weights than the control, with FertiGroe®-N-treated plants having higher root weights at all growth stages. At VT, IPB Var 6 had a lower root weight compared with NK8840 EZ Refuge in the urea treatment, and at R_1, it showed lower root weight in both urea and FertiGroe®-N treatments (Fig. 7a).

Longest root length

Root elongation is essential in penetrating the soil for nutrient and water absorption. Corn roots continuously elongated from V_6 to R_1 (Fig. 7b) and were influenced by both variety and N source. Variety NK8840 EZ Refuge exhibited the highest root length across sampling times and N sources, while IPB Var6 had a statistically similar root lengths at V_6 under FertiGroe®-N and control treatments, and at R_1 under the urea treatment. Root length appeared to be a plastic response of roots controlled by genotype and N source, with FertiGroe®-N enhancing root elongation of all three varieties tested. Variety NK8840 EZ Refuge had the longest root length while Pearl White had the shortest root across N source treatments and sampling times.

In this study, the plasticity of root characters in response to environmental conditions or nutritional N status was observed, including modulation of the length and density of root hairs and lateral roots as well as the development of adventitious roots or crown roots that contribute to increased root weight and root volume. Figs. 8 and 9 show plants treated with FertiGroe®-N had more improved length and number of root hairs compared with other treatments. This was a response to draw and deliver more water and nutrients for growing plant organs. At 30 DAP and tasseling, FertiGroe®-N had better root phenotype than other treatments.

Notably, Pearl Sweet had fewer root hairs and lateral roots than other varieties. Fig. 9 shows that among the varieties, NK8840 had more root hairs and more developed crown roots at R_1.

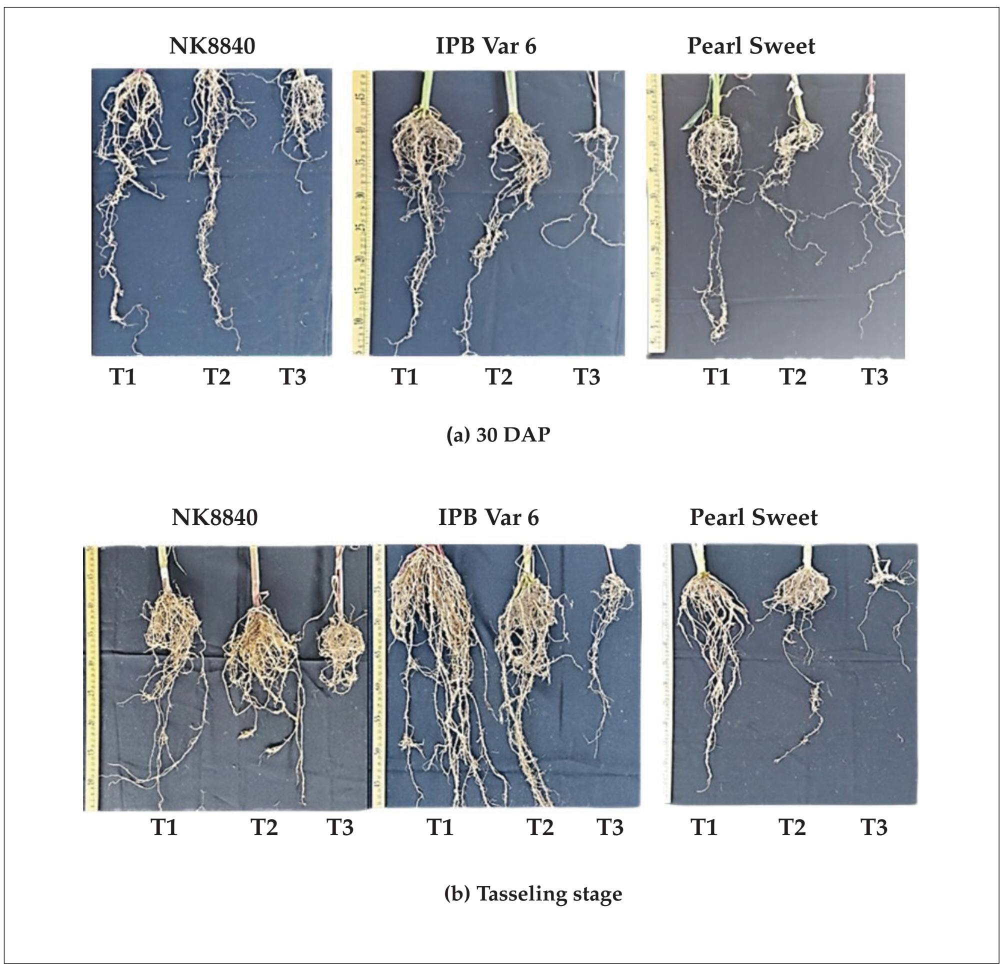


Fig. 8. Roots of different genotypes. V1-NK8840 EZ Refuge, V2-IPB Var 6, and V3- Pearl Sweet at (a) 30 DAP and (b) tasseling stage with different N sources (T1-FertiGroe®-N, T2-urea, T3-No nitrogen) grown in PVC tubes.

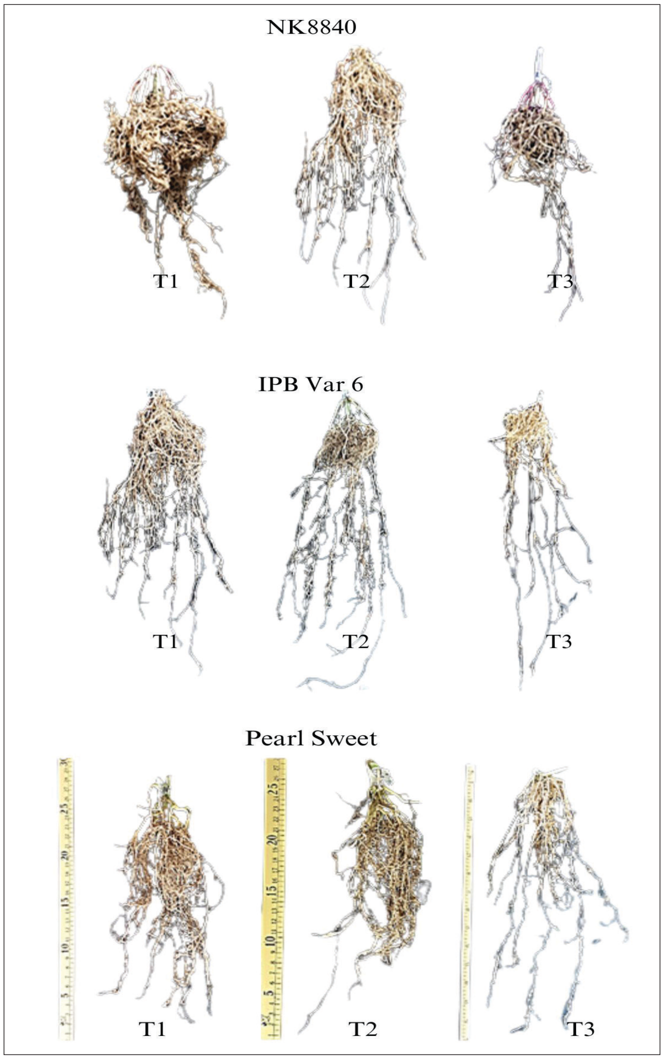


Fig. 9. Roots of (a) NK8840, (b) IPB Var 6, (c) Pearl Sweet at baby corn harvesting stage with different N sources (T1- FertiGroe®-N, T2- Urea, T3- No nitrogen) in PVC tubes.

Root base diameter

A well-developed root base diameter is significant in holding root systems and providing tolerance to lodging. Variety NK8840 had the thickest root base diameter across all N sources at V_6 and at all stages under the FertiGroe®-N treatment. Variety IPB Var 6 had the thickest root diameter at VT in both FertiGroe®-N and urea treatments and at R_1 under urea and control treatments (Fig. 10).

Root volume reflects the weight, length, and diameter of roots. Consistently, the highest root volumes were observed in plants treated with FertiGroe®-N (25 mL), followed by urea (16 mL) and control at V_6 (Fig. 10b). Variety NK8840 EZ Refuge had the highest root volume across growth stages, which was statistically similar with IPB Var 6 at V_6 and VT in FertiGroe®-N and urea treatments. Generally, Pearl Sweet had the lowest root volume across sampling times and N sources. The results suggest that FertiGroe®-N is effective in enhancing root traits. Root trait responses such as root weight, root length, and root volume demonstrated the availability and efficiency of FertiGroe®-N to release N even at a later stage. Moreover, the study clearly demonstrated that root responses to N sources differed among varieties.

Nitrogen source and variety influence root plasticity. Application of FertiGroe®-N resulted in better root weight, root length, root diameter, and root volume compared with other N sources. Likewise, genotypes also affect the variability in root traits. Generally, NK8840 EZ Refuge had the highest root weight, root volume, root length, and root diameter when applied with FertiGroe®-N. A higher root weight resulted in a higher root-shoot ratio in PVC tubes due to the inhibition of growth at VT and R_1. Generally, plasticity to restricted growth in plants with N showed stimulation of root hairs and lateral growth but deformed and reduced weight in brace roots. To adapt to nutrient limitations, plants often adjust their root morphology to access a larger soil volume for nitrogen resources (Sun et al. 2020). This may explain why a well-developed root system is frequently associated with efficient nitrogen utilization in crops (Yu et al. 2021). The root responses likely reflect different strategies to cope with N availability. Clearly, the N absorbed from FertiGroe®-N promoted nutrient uptake as evident in root weight and root volume. A vigorous root system is not only essential in anchorage and lodging resistance but also vital for shoot growth and leaf development during early vegetative growth (Walne and Reddy 2022). Thus, varieties that had exemplary root traits produced the highest plant height, stem width, chlorophyll content, LA, biomass, and ear shoot yield.

Prolific lateral roots in varieties applied with N were observed, which can have an association with N uptake. A study by Postma et al. (2014) showed that in corn, varieties with sparse distribution and long lateral roots are best for nitrate uptake.

Differences in the absorption, transportation, and metabolism of nitrogen between FertiGroe®-N and urea may account for variations in the response to nitrogen. Urea application has 20% – 40% losses due to leaching, volatilization, and surface runoff (Taradfer et al. 2020). FertiGroe®-N is coated with nanoparticles; thus, it is gradually released into the soil, creating timely nutrient utilization by the plants and consequently minimizing losses. Taradfer et al. (2020) found that nanofertilizers released nutrients more consistently than conventional urea, ensuring sustained nutrient availability for plants. This prolonged nutrient release promotes healthier plant growth compared with traditional fertilizers. Nanoparticles are negatively-charged, resulting in higher transport efficiency (Zhu et al. 2012), thus increasing N and improving growth. This implies that environmental conditions and properties of nanoparticles are important in understanding their influences on plants.

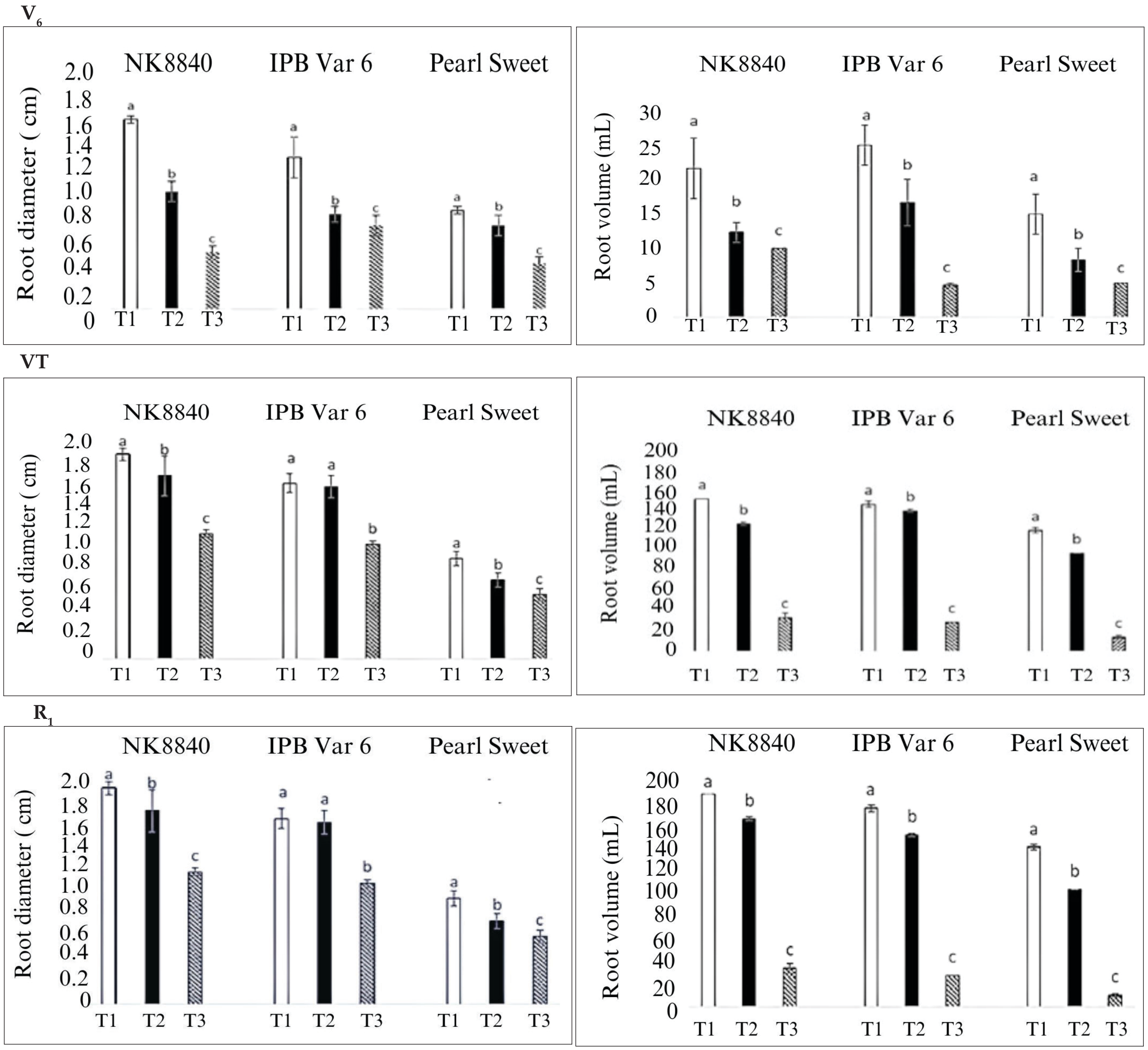


Fig. 10. Effects on (a) root diameter and (b) root volume of different N sources at different growth stages. (T1- FertiGroe®-N, T2-urea, T3-no nitrogen, V1- NK8840 EZ Refuge, V2- IPB Var 6, and V3- Pearl Sweet). Means within columns with the same letter(s) are not significantly different at 0.05 level of significance using LSD. Vertical bars represent standard error of means (*n* = 3).

High nutrient efficiency varieties are essential for achieving high yields and reducing fertilizer inputs in corn production. The N content in leaves at different growth stages affects the quality of ear shoot dry matter. Further research can focus on understanding the role of more effective nutrient use efficiency in improving growth parameters and yields for varieties grown for both forage and food.

CONCLUSION

Evaluating the effects of FertiGroe®-N and urea fertilizers on the morpho-physiological traits of three corn varieties (NK 8840, IPB Var 6, and Pearl Sweet) grown for food (ear shoots) and forage (baby corn fodder) showed that FertiGroe®-N enhanced plant height, leaf area, chlorophyll content, stalk width, root traits, and total dry matter from V_6 to R_1. Root biomass also significantly improved through treatment with FertiGroe®-N even at a later stage of crop development, resulting in improved ear shoot and forage yields. Applying FertiGroe®-N at a rate of 160 kg N is effective in enhancing these growth parameters across all three varieties and in all growth stages. These results also establish the role of slow-release nanofertilizers such as FertiGroe®-N in improving nutrient availability, promoting robust root development, and significantly boosting corn productivity and resilience. As the agricultural industry continues to seek sustainable solutions to meet the growing food demand, understanding and leveraging the relationship between root plasticity and nanofertilizers will be key to successful corn cultivation in the future. Further research on the potential use of FertiGroe®-N to improve nutrient use efficiency of corn varieties with differing root characteristics and plasticity is recommended.

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