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Research Article

Impact of Plant Population and Split Nitrogen Management on Nutrient Partitioning of Quality Protein Maize (*Zea mays* L.)

ARJU SAHID AHMED AND PARTHA SARATHI PATRA*

Department of Agronomy, Uttar Banga Krishi Viswavidyalaya, Pundibari, Cooch Behar-736165, West Bengal

ABSTRACT

A field experiment has been conducted during *rabi* season of 2021-22 and 2022-23 in the instructional farm of Uttar Banga Krishi Viswavidyalaya, West Bengal to study the Impact of plant population and split nitrogen management on nutrient partitioning of Quality Protein Maize (*Zea mays* L.). The experiment was laid out in a split-plot design with three main plots and five sub-plot treatments and was replicated four times. The main plot treatment consists of three different plant population, viz; PP_1- 55,555 plants ha^{-1}, PP_2 - 80,000 plants ha^{-1}, PP_3 - 1,25,000 plants ha^{-1}. The sub plot treatment consists of five split nitrogen management, like, SNM_1- Conventional nitrogen management, SNM_2 - 25% at basal + 25% at eight leaf stage + 25% at tasseling + 25% at silking, SNM_3- 20% at basal + 20% at eight leaf stage + 40% at tasseling + 20% at silking, SNM_4 - 20% at basal + 20% at eight leaf stage + 30% at tasseling + 30% at silking, SNM_5 - 10% at basal + 20% at eight leaf stage + 40% at tasseling + 30% at silking. Results revealed that N, P & K content of leaf and stem was found highest in PP_1 (55,555 plants ha^{-1}), followed by PP_2 (80,000 plants ha^{-1}) and least in PP_3 (125,000 plants ha^{-1}), But highest N, P & K uptake was observed in PP_3, due to a higher number of plants ha^{-1}. Total (leaf + stem + grain) nutrient uptake (kg ha^{-1}) was also observed to be highest in PP_3 and least in PP_1. Apart from that, whenever nitrogen was applied in four splits, i.e., 10% as basal +25% at the eight-leaf stage + 40% at tasseling +25% at silking (SPNM5), it recorded significantly higher N, P & K content and uptake in both years of experimentation. Total (leaf + stem + grain) nutrient uptake (kg ha^{-1}) was also observed to be highest in SPNM5, followed by SPNM3, and lowest in $SPNM_1$.

Key words: Plant population, Split nitrogen management, Nutrient partitioning, Quality protein maize

Introduction

Maize (*Zea mays* L.) is among the most important cereal crops globally and plays a key role in supporting food security, particularly in developing countries. In India, maize ranks as the third most critical staple crop after rice and wheat. However, conventional maize is deficient in essential amino acids like lysine and tryptophan, which are necessary for protein synthesis. This deficiency results in low protein quality, malnutrition, and reduced biological value due to poor net protein utilization.

Quality Protein Maize (QPM) resembles conventional maize in terms of grain texture, taste, and color, but it contains approximately double the lysine (4%) and tryptophan (0.8%) levels. This enhanced amino acid profile contributes to a higher biological value, making proteins in QPM more bioavailable to humans and animals than those in conventional maize (Jena *et al*., 2013). Additionally, QPM maintains high yield potential and resilience to biotic and abiotic stresses. Given its improved

*Corresponding author,
Email: parthaagro@gmail.com

protein content and cultivation requirements like those of conventional maize, QPM serves as an affordable protein source that can be readily integrated into traditional farming and consumption practices.

Nutrient partitioning in maize and cereal crops is vital for enhancing yield, grain quality, and sustainability. It involves allocating nutrients like nitrogen, phosphorus, and potassium to key plant parts (stems, leaves, and grains) throughout growth stages, optimizing development and resource use. Effective partitioning channels nutrients to grains during reproductive phases, supporting kernel filling and improving yield. This also boosts grain quality (e.g., protein, starch) critical for food and feed uses. By directing nutrients efficiently, plants minimize losses to the environment, reducing pollution and fertilizer dependency, and thus lowering the environmental impact. Additionally, nutrient partitioning improves crop resilience to stresses like drought, allowing nutrient allocation to critical parts under adverse conditions. Understanding nutrient partitioning informs precise fertilizer application, aligning with growth stages to enhance performance and reduce waste.

Nutrient partitioning is central to sustainable cereal crop production, as it helps maximize yield and quality, improves nutrient-use efficiency, supports environmental sustainability, and contributes to the economic viability of agricultural systems. Research and technologies that enhance our understanding and control of nutrient partitioning are crucial for developing resilient, productive crop varieties that meet the needs of a growing global population.

Maintaining optimal plant population is critical for maximizing solar radiation interception, which supports photosynthesis and efficient use of soil resources, such as nutrients and moisture. When plant populations per unit area exceed the optimal density, excessive inter- and intra-plant competition arises. This competition can restrict access to essential resources such as sunlight, water, and nutrients and may increase the risk of crop lodging. Therefore, achieving an ideal plant density is fundamental for sustaining high grain yields and enhancing protein quality in crops.

Nitrogen is a key factor in determining maize yield. Insufficient soil nitrogen reduces leaf area, limits photosynthetic rates, and delays plant growth and development, all of which lead to lower yields. Conversely, excessive nitrogen application increases production costs and contributes to environmental pollution, as it contaminates groundwater and releases nitrous oxide, a greenhouse gas, through volatilization, thus exacerbating global warming. To achieve optimal yields and enhance nitrogen use efficiency, real-time nitrogen application is essential.

Hence, to improve the dissemination and adoption of QPM hybrids, it is necessary to understand the performance of QPM under various agronomic management practices, among which split nitrogen management and plant population are important aspects. Focusing on maize cultivation in West Bengal, India, this study empirically investigates the effects of plant population and variable nitrogen management on nutrient partitioning in quality protein maize.

Materials and Methods

The experiment was carried out in a Split-Plot Design (SPD) with three main-plot treatments and five sub-plot treatments, with three replications. Details of the experiment are given below. The main plot treatment consists of three different plant populations, viz., PP1 - 55,555 plants ha^{-1}, PP_2 - 80,000 plants ha^{-1}, PP_3 - 1,25,000 plants ha^{-1}. The sub plot treatment consists of five split nitrogen management, like, SNM_1- Conventional nitrogen management, SNM_2 - 25% at basal + 25% at eight leaf stage + 25% at tasseling + 25% at silking, SNM_3- 20% at basal + 20% at eight leaf stage + 40% at tasseling + 20% at silking, SNM_4 -(20% at basal + 20% at eight leaf stage + 30% at tasseling + 30% at silking, SNM_5- 10% at basal + 20% at eight leaf stage + 40% at tasseling + 30% at silking. Conventional nitrogen management in the experimental area, as practised by farmers, is 50% as basal + 25% at the knee-high stage + 25% at tasseling.

For sowing, healthy, fully matured, and bold seeds of the VL QPM hybrid 59 were selected. This variety has a growth duration of approximately 140-155 days, is resistant to Turcicum leaf blight (TLB) and Maydis leaf blight (MLB), and offers a yield potential of 6.5-7.5 t ha^{-1}.

Among the nutrient analyses, nitrogen content was determined using the Modified Kjeldahl method (Jackson, 1967). Phosphorous content by Bray's method- Bray and Kurtz, 1945 (Jackson, 1967), and Potassium content by Flame photometer method (Jackson, 1967).

All data collected during the investigation were analyzed statistically using analysis of variance (ANOVA) for a split-plot design, employing the statistical software R (version 4.3.3) to calculate critical differences and standard error of the mean. A pooled analysis over two years was also conducted, following the methodology of Gomez and Gomez (1983). Results are presented at a 5% significance level (P=0.05).

Results and Discussions

Nitrogen content (%) of (leaf, stem, and leaf + stem)

The study revealed that plant population significantly affects nitrogen content in leaves, stems, and the combined leaf-stem nitrogen content (LNC, SNC, and L+SNC). Among the treatments, PP_1 (55,555 plants ha^{-1}) consistently had the highest nitrogen content in both years and in the pooled data. Specifically, PP_1 recorded an average LNC of 0.58, SNC of 0.19, and L+SNC of 0.77. In comparison, the densest planting geometry, PP_3 (1,25,000 plants ha^{-1}), had the lowest nitrogen content with values of 0.30 for LNC, 0.11 for SNC, and 0.41 for L+SNC (Fig. 1).

This trend aligns with findings by Choudhary *et al.* (2017), who reported that wider plant spacing improves nitrogen assimilation by reducing intraspecific competition for nutrients. In dense plantings (PP_3), limited space and resources per plant likely resulted in reduced nitrogen uptake. The significantly higher LNC, SNC, and L+SNC observed in PP_1 can be explained by reduced competition, which allows individual plants better access to available nitrogen. In comparison, denser spacings result in a lower nitrogen concentration per plant due to increased nutrient competition, which limits each plant's nitrogen assimilation capacity.

Among the nitrogen management treatments, SNM_5 (10% at basal, 20% at the eight-leaf stage, 40% at tasseling, 30% at silking) showed the highest nitrogen content across both years and, in the pooled analysis, with LNC at 0.51, SNC at 0.19, and L+SNC at 0.70.

Incremental nitrogen application in NM_5 at critical growth stages (tasseling and silking) appears effective in enhancing nitrogen uptake in both the leaf and stem, possibly due to improved nitrogen availability when plant demand is highest. These results align with studies that show delayed nitrogen applications maximize leaf nitrogen uptake during key growth stages (Zhang *et al.,* 2021).

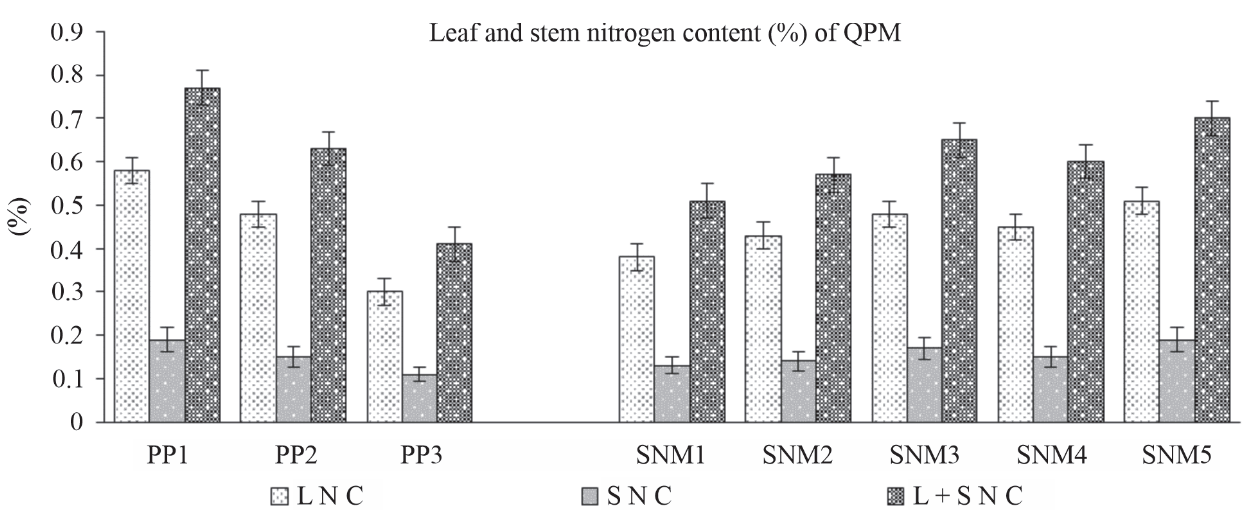

Fig. 1. Leaf nitrogen content (LNC), stem nitrogen content (SNC) and leaf + stem nitrogen content (L+SNC) of quality protein maize

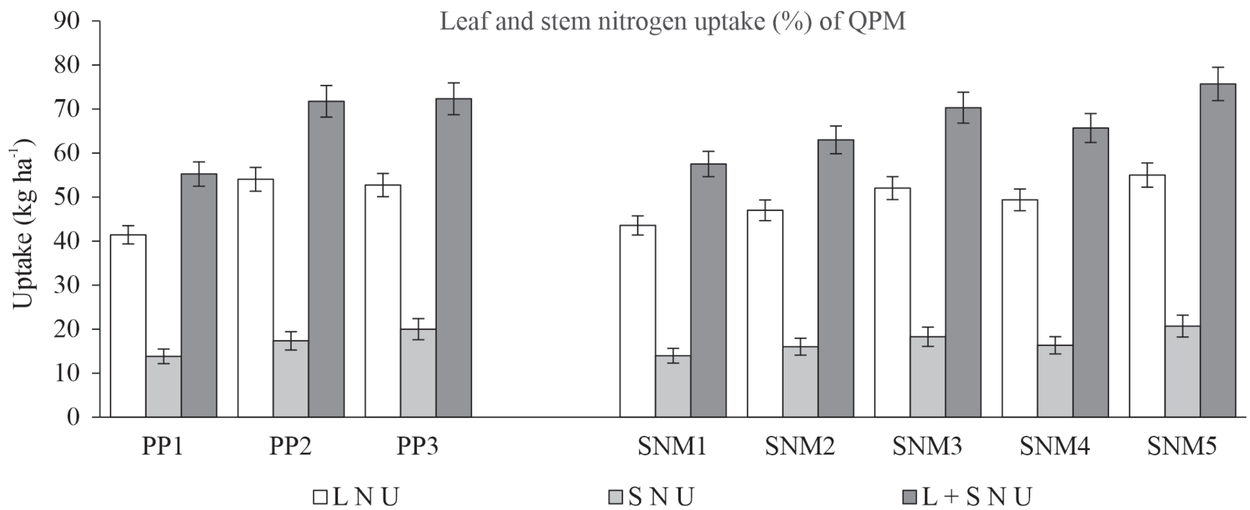

Fig. 2. Leaf nitrogen uptake (LNU), stem nitrogen uptake (SNU) and leaf + stem nitrogen uptake (L+SNU) of quality protein maize

Nitrogen uptake (kg ha^{-1}) of (leaf, stem and leaf + stem)

Data presented in Fig. 2 revealed that plant population significantly affects nitrogen content across leaf, stem, and combined leaf-stem nitrogen uptake (LNU, SNU, and L+SNU). The PP_3 density (125,000 plants ha^{-1}) recorded the maximum pooled LNU (52.72 kg ha^{-1}), SNU (19.99 kg ha^{-1}), and L+SNU (72.32 kg ha^{-1}). This was followed by PP_2 (80,000 plants ha^{-1}) with LNU (54.03 kg ha^{-1}), SNU (17.34 kg ha^{-1}), L+SNU (71.74 kg ha^{-1}) and lowest in PP_1 (125,000 plants ha^{-1}) with LNU (41.43 kg ha^{-1}), SNU (13.82 kg ha^{-1}), L+SNU (55.23 kg ha^{-1}).

The study suggests that closer plant spacing (PP_2 and PP_3), which increases plant density, boosts competition among plants, leading to higher nitrogen uptake in leaves and stems. This intensified competition enhances root nitrogen absorption, supporting photosynthesis and growth. Denser configurations promote nitrogen concentration in stems, acting as nitrogen reservoirs to support grain filling under high-density conditions. These findings align with Zhang *et al.* (2020), who reported similar benefits of high-density planting on nitrogen uptake and allocation.

Among the nitrogen treatments, SNM_5 (10% basal, 20% at eight leaf stage, 40% at tasseling, 30% at silking) achieved the highest LNU (54.99 kg ha^{-1}), SNU (20.69 kg ha^{-1}), L+SNU (75.69 kg ha^{-1}). followed by SNM_3, LNU (52.03 kg ha^{-1}), SNU (18.27 kg ha^{-1}), L+SNU (70.30 kg ha^{-1}). The lowest uptake was observed in SNM_1, LNU (43.55 kg ha^{-1}), SNU (13.96 kg ha^{-1}), and L+SNU (57.51 kg ha^{-1}).

Nitrogen uptake in SNM_5 aligns with findings by Cai *et al.* (2019), who found that synchronized nitrogen applications during critical growth stages elevate nitrogen use efficiency by enhancing nitrogen assimilation in the leaves, where photosynthetic activity is high. Further, he also indicated that efficient nitrogen mobilization in stems supports reproductive growth, crucial during late vegetative and reproductive stages. By timing nitrogen applications to coincide with tasseling and silking stages, the plants in SNM_5 likely improved nitrogen translocation to stems, enhancing support for grain development. Choudhary *et al.* (2017) reported that split nitrogen applications aligned with growth stages improve nitrogen recovery rates by reducing losses due to leaching or volatilization, thus enhancing nitrogen use efficiency and supporting higher biomass and grain yields.

Phosphorus content (%) of (leaf, stem, and leaf + stem)

The PP_1 plant density (55,555 plants ha^{-1}) had the highest phosphorus levels: leaf phosphorus at 0.18%, stem phosphorus at 0.13%, and total phosphorus at 0.30%. PP_2 (80,000 plants ha^{-1})

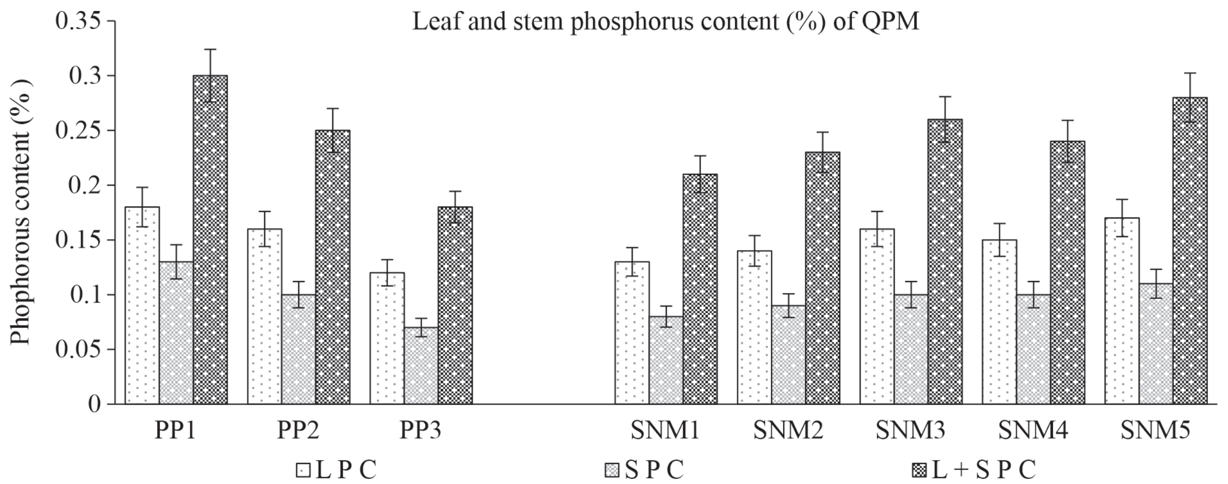

Fig. 3. Leaf phosphorus content (LPC), stem phosphorus content (SPC) and leaf + stem phosphorus content (L+SPC) of quality protein maize

followed with leaf, stem, and total phosphorus contents of 0.16%, 0.10%, and 0.25%, respectively. PP_3 (125,000 plants ha^{-1}), the densest spacing, had the lowest phosphorus levels, with leaf at 0.12%, stem at 0.07%, and total at 0.19% (Fig. 3).

This trend suggests that wider plant spacing, like in PP_1, reduces competition for soil nutrients, enabling higher phosphorus uptake, especially in leaves, which is vital for photosynthesis. Similar findings (Lee and Park, 2020) indicate that lower-density planting improves phosphorus availability and uptake in both leaves and stems. In contrast, denser plantings face more competition, limiting phosphorus availability and reducing its allocation to stems (Johnson *et al.,* 2018).

Nitrogen management treatment SNM_5 (10% basal, 20% at eight leaf stage, 40% at tasseling, 30% at silking) achieved the highest phosphorus levels across all parameters. leaf phosphorus content (LPC) at 0.17%, stem phosphorus content (SPC) at 0.11%, and total phosphorus at 0.28%. SNM_3 and SNM_4 followed closely, each with LPC of 0.16% and SPC of 0.10%. SNM_1 had the lowest values, with LPC at 0.13%, SPC at 0.08%, and total phosphorus at 0.21%.

These findings show that the timing of nitrogen applications affects phosphorus uptake, likely by enhancing root growth and nutrient absorption. Aligning nitrogen applications with peak demand stages (tasseling and silking), as in SNM_5, improves phosphorus uptake, with higher LPC and SPC due to efficient nutrient assimilation during critical growth phases. Research by Wang et al. (2021) supports the idea that staggered nitrogen applications increase nutrient use efficiency, biomass, and phosphorus allocation, leading to higher total phosphorus in SNM_5.

Phosphorus uptake (kg ha^{-1}) of (leaf, stem, and leaf + stem)

Plant population PP_3 had the highest leaf phosphorus uptake (20.56 kg ha^{-1}) and stem phosphorus uptake (11.47 kg ha^{-1}), resulting in the highest total phosphorus uptake (32.02 kg ha^{-1}). PP_2 followed with 17.72 kg ha^{-1} for leaves, 10.70 kg ha^{-1} for stems, and 28.42 kg ha^{-1} in total. PP_1 had the lowest phosphorus uptake across all metrics (Figure 4).

The results suggest that denser planting (PP3) increases phosphorus uptake by boosting root density, enhancing nutrient access. Li *et al.* (2018) found that higher root mass in dense plantings improves phosphorus absorption, supporting higher LPU of PP3. Increased SPU in dense configurations may stem from greater phosphorus demand due to rapid growth and biomass accumulation, as shown by Smith and Johnson (2020). This higher total uptake indicates that phosphorus is a limiting factor in dense setups, consistent with Wang *et al.* (2019), who found that dense spacing drives nutrient uptake to support growth.

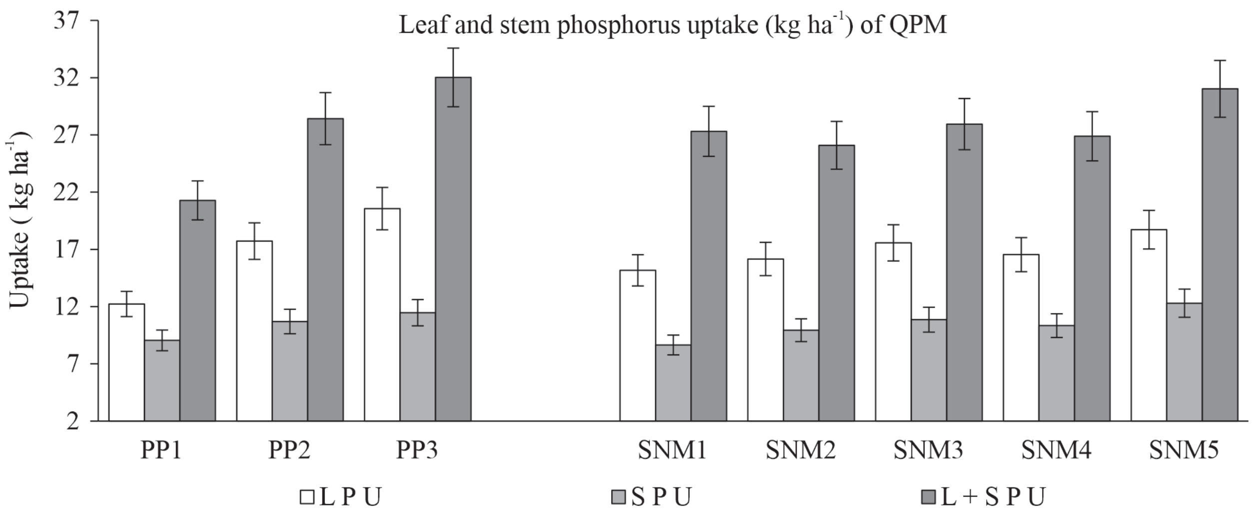

Fig. 4. Leaf phosphorus uptake (LPU), stem phosphorus uptake (SPU) and leaf + stem phosphorus uptake (L+SPU) of quality protein maize

SNM_5 (10% basal, 20% at eight leaf stage, 40% at tasseling, 30% at silking) recorded the highest pooled LPU at 18.72 kg ha^{-1}, followed by SNM_3 (17.57 kg ha^{-1}), and SNM_1 had the lowest LPU (15.17 kg ha^{-1}). Stem phosphorus uptake followed a similar pattern, with SNM_5 achieving the highest pooled SPU at 12.30 kg ha^{-1}, followed by SNM_3 (10.86 kg ha^{-1}), while SNM_1 recorded the lowest SPU (8.65 kg ha^{-1}). Total phosphorus uptake was also highest in SNM_5 (31.02 kg ha^{-1}), followed by SNM_3 (27.94 kg ha^{-1}), while SNM_1 had the lowest at 27.31 kg ha^{-1}.

The SNM_5 nitrogen application strategy, with timing aligned to maize growth stages, likely boosted phosphorus uptake by enhancing root development during peak demand periods (tasseling and silking). This approach supports nutrient allocation to structural tissues, strengthening stems and optimizing plant resilience. Prior studies by Zhao *et al.* (2020) and Chao *et al.* (2019) similarly found that well-timed nitrogen applications improve phosphorus uptake and stem development. Lee and Park (2021) further noted that staggered nitrogen timing promotes nutrient synergy, maximizing nutrient use efficiency and uptake.

Potassium content (%) of (leaf, stem, and leaf + stem)

Maximum plant population (PP_1) produced the highest potassium content in both maize leaves (0.78%) and stems (0.54%), with total potassium content (L + S KC) reaching 1.31% (Fig. 5). In comparison, intermediate plant population (PP_2) had lower values (LKC 0.62%, SKC 0.44%), and the densest plant population (PP_3) recorded the lowest potassium levels (LKC 0.46%, SKC 0.30%, total 0.76%).

A lesser plant population improves potassium uptake by reducing competition, allowing each plant more access to soil nutrients. Chen *et al.* (2020) found that increased spacing enhances individual potassium absorption, essential for photosynthesis and enzyme function. As plant density rises, potassium uptake efficiency tends to drop due to intensified competition (Zhao *et al.,* 2022). In denser plantings like PP_3, potassium availability for structural tissues declines, impacting stem rigidity (Liu *et al.,* 2020). Higher combined leaf and stem potassium content of PP_1 reflects better nutrient accumulation and root development due to less competition. Parker *et al.,* (2021) confirmed that lowest plant population supports root spread and potassium absorption, benefiting plant health.

The SNM_5 treatment, (10% at basal, 20% at eight leaf stage, 40% at tasseling, and 30% at silking), resulted in the highest potassium content in both leaves (0.65%) and stems (0.47%) and TKC (1.11%). In contrast, SNM_1, with a simpler nitrogen schedule (50% at basal, 25% at knee height, 25% at tasseling),

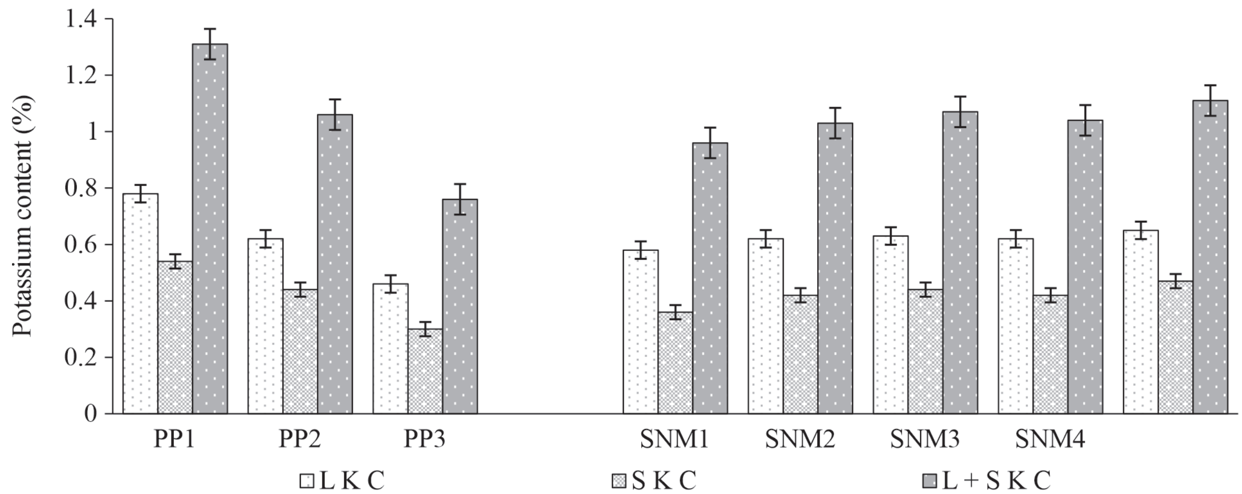

Fig. 5. Leaf potassium content (LKC), stem potassium content (SKC) and leaf + stem potassium content (L+SKC) of quality protein maize

had the lowest potassium levels in leaves (0.58%) and stems (0.36%) and TKC (0.96%).

Splits nitrogen application in treatment SNM_5 promotes root development and nutrient uptake, especially during peak growth stages such as tasseling and silking. This approach, supported by Zhang and Li (2021), aligns nitrogen supply with growth needs, boosting potassium uptake through increased root surface area. Wang *et al.* (2022) also noted that stage-specific nitrogen applications enhance overall macronutrient absorption, particularly potassium, by improving root activity. Liu *et al.* (2020) further highlighted that well-timed nitrogen applications optimize potassium use by reducing leaching and increasing root absorption. This synergy in SNM_5 improves potassium uptake efficiency.

Potassium uptake (kg ha^{-1}) of (leaf, stem, and leaf + stem)

Plant population significantly impacted potassium uptake, with the PP_3 (125,000 plants ha^{-1}) showing the highest leaf potassium uptake (LKU) at 82.66 kg ha^{-1}, followed by PP_2 (80,000 plants ha^{-1}) at 70.64 kg ha^{-1}, and PP_1 (55,555 plants ha^{-1}) at 55.39 kg ha^{-1}. Stem potassium uptake (SKU) was also highest in PP_3 at 53.30 kg ha^{-1}, with PP_2 at 50.23 kg ha^{-1} and PP_1 at 38.24 kg ha^{-1}. Total potassium uptake (L + S KU) was highest in PP_3 at 126.95 kg ha^{-1}, showing the benefits of denser plant population for potassium uptake (Fig. 6).

Higher plant density enhances potassium uptake by increasing root volume per hectare, thereby boosting nutrient extraction. Jones *et al.* (2020) found that denser planting expands root networks, raising total nutrient uptake despite greater competition per plant. Similarly, Patel *et al.* (2021) observed that dense planting promotes nutrient translocation to structural tissues, driven by higher demand. The higher SKU in PP_3 may stem from increased root interaction, improving nutrient flow. Zhang *et al.* (2021) also noted that optimal planting density boosts nutrient uptake efficiency, though soil nutrients should be managed to prevent depletion.

Among nitrogen management practices, SNM_5 (10% basal, 20% at the eight-leaf stage, 40% at tasseling, 30% at silking) showed the highest leaf potassium uptake (LKU) of 71.52 kg ha^{-1} and stem potassium uptake (SKU) of 51.17 kg ha^{-1}. This resulted in the highest total potassium uptake (L + S KU) of 122.69 kg ha^{-1}. In contrast, SNM_1 (50% basal, 25% at knee height, 25% at tasseling) had the lowest values, with 67.27 kg ha^{-1} for LKU, 43.55 kg ha^{-1} for SKU, and a total of 110.82 kg ha^{-1}.

Split nitrogen application of SNM_5 sustains nitrogen availability through key growth stages, enhancing potassium uptake efficiency. Li *et al.* (2019) found that staggered nitrogen applications

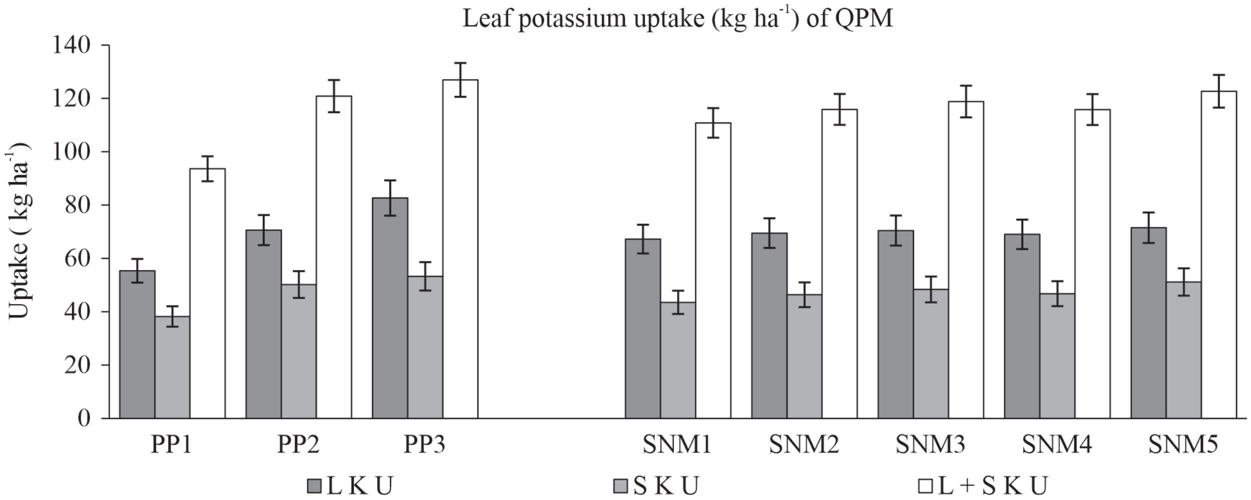

Fig. 6. Leaf potassium uptake (LKU), stem potassium uptake (SKU) and leaf + stem potassium uptake (L+SKU) of quality protein maize

reduce leaching and support nutrient uptake by maintaining root function. The higher SKU in SNM_5 likely results from nitrogen availability during phases like eight leaf stage, tasseling, and silking, which supports potassium translocation to stems. Wang and Zhao (2021) noted similar benefits for nutrient translocation in potassium-demanding crops, and Singh *et al.* (2022) showed that distributed nitrogen applications optimize nutrient absorption by keeping roots active longer.

Total nutrient uptake (kg ha^{-1}) of (grain + leaf + stem)

The plant population demonstrated a pronounced influence on nutrient uptake, with the population density of PP_3 (125,000 plants ha^{-1}) exhibiting the most significant results. In terms of total nitrogen uptake (TNU), PP_3 recorded a significantly higher value of 220.04 kg ha^{-1}, which represents a 17.9% enhancement compared to the lower population density of PP_1 (55,555 plants ha^{-1}). Similarly, PP_3 achieved the highest total phosphorus uptake (TPU), measured at 67.14 kg ha^{-1}, surpassing PP_1 by 30.7%. Furthermore, PP_3 outperformed other population densities in total potassium uptake (TKU), reaching 211.78 kg ha$^{-1,}$ a substantial increase of 34.2% compared to PP_1. These findings underscore the critical role of plant population density in optimizing nutrient absorption efficiency in agricultural systems (Table 1).

The elevated nitrogen uptake observed in PP_3 can be attributed to improved root-soil interactions, which facilitate greater nitrogen uptake, particularly under intensified inter-plant competition (Chand *et al.,* 2021). The closer plant spacing characteristic of PP_3 increases leaf area index (LAI), which in turn elevates the overall nitrogen demand to support expanded photosynthetic activity and biomass production (Chen *et al.,* 2019). Similarly, the higher phosphorus uptake in PP_3 is closely associated with more extensive root proliferation. This enhanced root system enables plants to access phosphorus, a relatively immobile nutrient in the soil, more efficiently in dense planting conditions (Zhao *et al.,* 2020). Furthermore, the increased potassium uptake in PP_3 highlights its critical role in maintaining cellular turgor pressure and ensuring efficient nutrient transport. This uptake is further supported by enhanced stomatal regulation and osmotic adjustments in densely populated stands, which collectively optimize the utilization of potassium for physiological functions (Patra *et al.,* 2022).

The SNM_5 nitrogen management strategy, characterized by the application of nitrogen in a phased manner 10% at the basal stage, 20% at the eight-leaf stage, 40% at tasseling, and 30% at silking resulted superior nutrient uptake efficiency. This approach resulted in the highest recorded values for total nutrient uptake, with total nitrogen uptake (TNU) reaching 232.73 kg ha^{-1}, total phosphorus

Table 1. Total nitrogen uptake (TNU), total phosphorus uptake (TPU) and total potassium uptake (TKU) of quality protein maize

Treatments	T N U (kg ha^{-1})			T P U (kg ha^{-1})			T K U (kg ha^{-1})		
	2021	2022	Pooled	2021	2022	Pooled	2021	2022	Pooled
Plant population									
PP_1	183.74	189.51	186.63	50.96	51.75	51.36	155.49	160.35	157.92
PP_2	208.86	218.28	213.57	58.92	61.19	60.06	190.43	194.47	192.45
PP_3	216.22	223.85	220.04	66.09	68.19	67.14	209.22	214.34	211.78
SE m (±)	0.82	1.06	0.67	1.39	0.90	0.83	1.02	1.35	0.85
CD (P=0.05)	3.21	4.14	2.18	5.45	3.52	2.69	4.01	5.29	2.76
Split nitrogen management									
SNM_1	174.94	182.19	178.57	49.36	49.93	49.65	168.16	173.56	170.86
SNM_2	192.91	202.31	197.61	55.71	56.97	56.34	179.86	186.87	183.37
SNM_3	213.93	222.21	218.07	61.36	65.21	63.29	191.64	194.77	193.21
SNM_4	203.78	209.70	206.74	59.54	58.47	59.01	186.14	187.82	186.98
SNM_5	229.13	236.32	232.73	67.30	71.29	69.30	199.44	205.58	202.51
SE m (±)	1.29	1.69	1.06	0.84	1.17	0.72	1.44	1.43	1.01
CD (P=0.05)	3.77	4.94	3.02	2.45	3.43	2.05	4.20	4.17	2.88

uptake (TPU) at 69.30 kgha^{-1}, and total potassium uptake (TKU) at 202.51 kg ha^{-1}. Compared to the lowest uptake levels observed under the SNM_1 strategy, these figures represent significant improvements of 30.3% in TNU, 39.6% in TPU, and 18.5% in TKU. These results underscore the effectiveness of SNM_5 in synchronizing nitrogen availability with critical growth stages, thereby maximizing nutrient absorption and utilization.

The nitrogen application strategy in SNM_5 is designed to synchronize nutrient availability with the critical growth stages of crop, thereby improving nitrogen uptake efficiency while reducing potential losses through leaching (Scharf & Lory, 2019). The targeted application of nitrogen during the tasseling and silking stages supports increased biomass production and maximizes yield potential by meeting the heightened nutrient demands during these phases (Subedi & Ma, 2021). Similarly, the timing of phosphorus application in SNM_5 aligns with key periods of root development and reproductive growth, ensuring optimal phosphorus availability when its demand is at its peak. Furthermore, the split application of potassium within the SNM_5 regime enhances water regulation and strengthens the stress tolerance capacity of crop, particularly in densely planted systems. This is consistent with findings that strategic potassium distribution improves both nutrient uptake efficiency and crop resilience in competitive environments (Santos *et al.,* 2020).

Conclusion

The study highlights that plant population and nitrogen management practices significantly influence nutrient uptake and productivity in maize, with tailored strategies enhancing resource use efficiency and yield potential. Specifically, the use of denser planting (PP_3) combined with staggered nitrogen applications (SNM_5) at critical growth stages (tasseling and silking) maximizes nitrogen, phosphorus, and potassium uptake. This approach aligns nitrogen availability with peak crop demand, promoting efficient nutrient absorption, biomass accumulation, and potentially higher grain yields.

In phosphorus-limited conditions, a wider spacing (PP_1) and SNM_5 application strategy demonstrated optimal phosphorus and potassium uptake, attributed to reduced competition among plants for soil resources. Lower plant populations in PP_1 enable better nutrient acquisition for each plant, facilitating phosphorus accumulation in leaf and stem tissues. The SNM_5 management aligns with crop growth stages to support root development and nutrient uptake, particularly enhancing the efficiency of phosphorus and potassium uptake.

Collectively, these results emphasize the value of selecting appropriate planting density and nitrogen management strategies to optimize nutrient uptake and promote sustainable maize production. Future studies could explore the long-term effects of these strategies on soil nutrient status, cycling, and environmental sustainability across various agroecological zones, thereby further refining crop management practices to enhance yield and ecological health.

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