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Economic Assessment of Quality Protein Maize Using Different Plant Geometry and Split Nitrogen Management Strategies

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***Abstract*—** *A field experiment was conducted during the rabi season (November-April) of 2021-22 and 2022-23 at the instructional farm of Uttar Banga Krishi Viswavidyalaya, West Bengal, aimed at evaluating the effects of plant geometry and split nitrogen management on the economic performance of Quality Protein Maize (Zea mays L.). The experimental setup employed a split-plot design with three main plot treatments for plant geometry and five sub-plot treatments for split nitrogen management, with each treatment replicated three times. The main plot treatments included three planting densities and sub-plot treatments contained five different split nitrogen management regimes. Results indicated that among the plant geometry treatments, the PG3 (40 x 20 cm spacing with 125,000 plants ha^{-1}) resulted in the highest cost of cultivation (78,081.49 and 80,865.09 Rs. ha^{-1}), but also achieved the highest gross returns (226,267.9 and 221,563.1 Rs. ha^{-1}), net returns (148,186.38 and 140,998.04 Rs. ha^{-1}), and benefit-cost ratios (2.90 and 2.75) over both years. In contrast, PG1 (60 x 30 cm spacing, 55,555 plants ha^{-1}) showed the lowest economic values, with a cost of cultivation of 73,681.49 and 76,165.09 Rs. ha^{-1}, gross returns of 145,736.7 and 143,451.8 Rs. ha^{-1}, net returns of 72,055.18 and 67,286.66 Rs. ha^{-1}, and a benefit-cost ratio of 1.98 and 1.88 during both years of experimentation. For nitrogen management, the SN5 treatment (10% at basal, 20% at V8, 40% at VT, and 30% at R1) led to significantly higher economic returns, recording gross returns of 193,258.8 and 187,730.6 Rs. ha^{-1}, net returns of 116,961.9 and 108,936.2 Rs. ha^{-1}, and benefit-cost ratios of 2.54 and 2.37. Conversely, the conventional nitrogen management (SN1) yielded the lowest economic outcomes, with gross returns of 173,216.5 and 169,693.3 Rs. ha^{-1}, net returns of 100,329.6 and 94,378.91 Rs. ha^{-1}, and benefit-cost ratios of 2.31 and 2.22 across both years.*

The study shows that cultivating Quality Protein Maize (QPM) with the VL QPM Hybrid 59, using a dense planting geometry of 40 x 20 cm (125,000 plants ha^{-1}), significantly enhances economic returns for farmers in North Bengal. This setup optimizes land use and productivity. Additionally, a strategic split nitrogen application (10% basal, 20% at V8, 40% at VT, and 30% at R1) aligns nitrogen availability with key growth stages, promoting optimal growth and yield. Together, these practices present an effective agronomic strategy to improve the profitability of maize farming in the region.

Keywords*— *quality protein maize, plant geometry, split nitrogen application, economics.

I. INTRODUCTION

Maize (Zea mays L.) is recognized as one of the most essential cereal crops worldwide, contributing significantly to food security, particularly in developing regions where it serves as a dietary staple. In India, maize holds a vital place as the third most important crop after rice and wheat, forming a core part of the national diet. However, conventional maize varieties are deficient in certain key amino acids, particularly lysine and tryptophan. These amino acids are fundamental for the synthesis of high-quality proteins in the human body. Due to this deficiency, the protein quality of traditional maize is relatively low, which can lead to malnutrition and a decrease in the biological value of the food, as the net protein utilization in the body is compromised. Consequently, this limitation impacts overall nutritional outcomes, particularly in populations that rely heavily on maize as a primary food source.

Quality Protein Maize (QPM) closely resembles traditional maize in appearance, taste, and grain texture, yet it offers a substantial improvement in nutritional content. Unlike standard maize, QPM contains nearly double the amounts of lysine (approximately 4%) and tryptophan (around 0.8%), two essential amino acids that enhance protein quality and availability. This increased amino acid concentration raises the biological value of QPM, meaning that the proteins it provides are more easily absorbed and utilized by humans and animals alike (Jena et al., 2013). Besides its nutritional benefits, QPM demonstrates a high potential for yields and is naturally resilient against various biotic stresses (like pests and diseases) and abiotic stresses (such as drought and poor soil conditions). With its improved protein profile and adaptability to conventional cultivation methods, QPM offers an affordable and practical protein source that fits seamlessly into existing farming systems. It holds particular promise as a sustainable food option in regions that rely on maize as a dietary staple, addressing protein deficiencies without requiring major changes to agricultural or dietary practices.

Achieving and maintaining an optimal plant population is essential for maximizing the capture of solar radiation, which directly supports photosynthesis and helps crops make the most of available soil resources, such as nutrients and moisture. When the number of plants per unit area surpasses the ideal density, it leads to intense competition both between and within individual plants. This excessive competition limits each plant's access to vital resources, including sunlight, water, and essential nutrients. Furthermore, high plant densities increase the likelihood of crop lodging, where plants bend or fall over, often due to weakened stems, making harvesting more challenging and reducing yield. Thus, establishing the ideal plant density is crucial not only for achieving high grain yields but also for promoting enhanced protein quality in crops. By optimizing plant spacing, farmers can better support crop health, resilience, and productivity, ultimately contributing to more sustainable and efficient agricultural practices.

Nitrogen plays a crucial role in driving yield outcomes in maize production, as it is a fundamental nutrient that supports various aspects of plant growth and development. When nitrogen levels in the soil are inadequate, plants suffer from reduced leaf area, which limits their ability to capture sunlight effectively, thereby lowering photosynthesis rates. This deficiency also hampers overall growth and slows down developmental stages, ultimately resulting in significantly reduced crop yields. On the other hand, excessive nitrogen use, while potentially boosting yields in the short term, comes with several drawbacks. High nitrogen applications increase production costs for farmers and pose environmental risks, as surplus nitrogen can leach into groundwater or volatilize into the atmosphere as nitrous oxide, a potent greenhouse gas that contributes to global warming. Achieving optimal yields while improving nitrogen use efficiency requires a balanced, real-time nitrogen application approach. This strategy allows for precise nitrogen delivery based on the crop's specific growth needs, maximizing yield potential, enhancing environmental sustainability, and ensuring that nitrogen resources are used effectively throughout the growing season. According to Patra et al. (2022), mid-November to the first week of December is the ideal time for maize sowing.

Optimizing crop geometry and nitrogen management is fundamental to enhancing the economic returns and productivity of quality protein maize (QPM) and conventional maize. These agronomic practices influence yield, input costs, nutrient use efficiency, and overall profitability, while also supporting environmental sustainability. This paper discusses the roles of optimal plant density and nitrogen application in maximizing protein quality of QPM and economic viability. Through an integrated approach, these practices enhance resource efficiency, improve grain quality, and reduce the risk of crop lodging, ultimately supporting sustainable agricultural systems.

To facilitate the broader dissemination and adoption of Quality Protein Maize (QPM) hybrids, it is essential to gain a deeper understanding of how QPM performs under different agronomic management practices. Among these practices, split nitrogen application and optimal plant population density are particularly important. By focusing on the cultivation of maize in West Bengal, India, this study aims to rigorously examine the effects of varying plant population densities and nitrogen management approaches on the nutrient partitioning and overall performance of QPM. The investigation seeks to determine how different levels of nitrogen, applied in a phased or split manner, and carefully managed plant spacing impact key growth metrics, nutrient uptake, and the protein quality of QPM. This research aims to provide practical insights for local farmers, enhancing QPM cultivation strategies that maximize yield and nutrient efficiency while addressing region-specific challenges.

II. MATERIALS AND METHODS

The experiment was conducted using a Split Plot Design (SPD) with three main plot treatments and five sub-plot treatments, replicated three times. The main plot treatments consisted of three different plant geometries: PG1 (60 x 30 cm) with a density of 55,555 plants ha^{-1}, PG2 (50 x 25 cm) with 80,000 plants ha^{-1}, and PG3 (40 x 20 cm) with 125,000 plants ha^{-1}. For sub-plot treatments, five nitrogen management strategies were tested: SN1 - conventional nitrogen management approach; SN2 - 25% nitrogen applied at basal, 25% at V8, 25% at VT, and 25% at R1; SN3 - 20% nitrogen applied at basal, 20% at V8, 40% at VT, and 20% at R1; SN4 - 20% nitrogen at basal, 20% at V8, 30% at VT, and 30% at R1; and SN5 - 10% nitrogen at basal, 20% at V8, 40% at VT, and 30% at R1. In this experimental area, the conventional nitrogen management commonly practiced by farmers involves applying 50% of nitrogen at basal, followed by 25% at the knee height stage and 25% at VT.

For sowing, carefully selected seeds of the VL QPM hybrid 59 were used, chosen for their health, full maturity, and robust size. This hybrid variety has a growth period of about 140 to 155 days and is noted for its resistance to two major diseases: Turcicum Leaf Blight (TLB) and Maydis Leaf Blight (MLB), which are common threats in maize production. Additionally, VL QPM hybrid 59 is recognized for its high yield potential, typically producing between 6.5 to 7.5 t ha^{-1} under optimal growing conditions. This variety not only ensures resilience against key diseases but also supports the objective of achieving substantial yield outputs in the experiment.

All data gathered throughout the study were statistically analyzed through analysis of variance (ANOVA) tailored for a split-plot design. This analysis was conducted using R software (version 4.3.3), allowing for precise calculation of critical differences and standard error of the mean to evaluate treatment effects. Additionally, a pooled analysis across two years was performed, adhering to the statistical methodology outlined by Gomez and Gomez (1983) to ensure robustness of results over time. The findings are reported at a 5% significance level (P=0.05), providing a reliable basis for interpreting treatment differences.

III. RESULTS AND DISCUSSION

3.1 Grain Yield (t ha^{-1}):

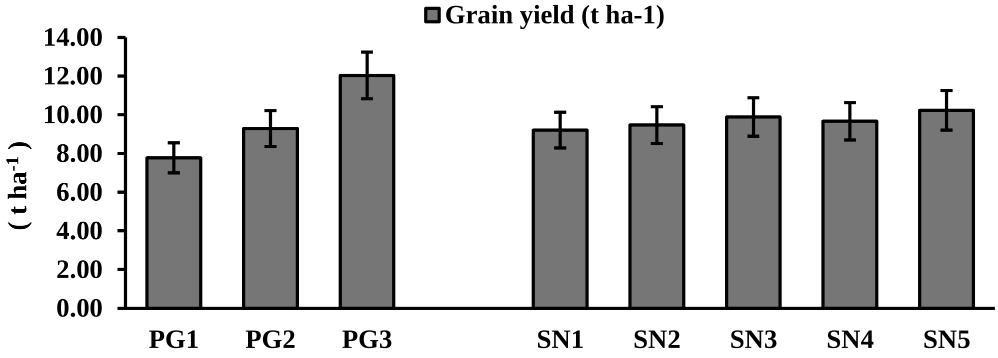

FIGURE 1: Graphical representation of grain yield (t ha^{-1}) of QPM as influenced by plant geometry and split nitrogen management.

Among crop geometry, significantly higher grain yield was observed in PG3 (12.03 t ha^{-1}) followed by PG2 (9.29 t ha^{-1}) and statistically lower grain yield was found in PG1 (7.77 t ha^{-1}) (pooled data of both years).

Among varying nitrogen management, grain yield varied significantly during both years of study. Significantly higher grain yield was observed in SN5 (10.23 t ha^{-1}) followed by SN3 (9.89 t ha^{-1}) and statistically lower grain yield was recorded in SN1 (9.21 t ha^{-1}) (pooled data of both years).

At lower planting densities, each maize plant can fully utilize the available resources, which generally leads to improved individual plant growth and better production attributes. When plant density is low, as in the case of 55,555 plants ha^{-1} (PG1), plants experience minimal competition for essential resources such as light, water, and nutrients. This favorable environment allows each plant to grow more robustly and produce larger, well-developed cobs. However, the reduced overall plant population also leads to a lower total cob count per hectare due to fewer plants. Increasing plant density from 55,555 to 125,000 plants ha^{-1} (PG3) results in a higher total number of cobs per unit area, as more plants contribute to cob production (IIMR, 2015a; IIMR, 2015e). However, this increase in plant population intensifies inter-plant competition for resources. Due to this competition, each individual plant produces smaller cobs, which can reduce per-plant yield. The increased competition particularly impacts the availability of resources such as nitrogen and water, crucial for cob development, thus leading to a decrease in the average cob size. At higher densities, mutual shading and crowding among plants increase, which negatively affects the growth of individual plants (Dar et al., 2014). This higher density fosters competition not only among neighboring plants but also between the vegetative (stalk and leaves) and reproductive (cob) parts within each plant, as both require substantial resources for development. Such competition can limit the availability of nutrients and energy for grain filling, potentially affecting the quality and weight of the cobs (Dutta et al., 2015). Interestingly, the PG3 treatment (40 x 20 cm spacing, 125,000 plants ha⁻¹) achieves the highest grain yield (t ha⁻¹) compared to the lower density configurations (PG1 and PG2). This outcome can likely be attributed to the higher total number of plants contributing to cob production per unit area.

The SN5 nitrogen management strategy, which involves applying nitrogen in a split pattern of 10% at basal, 20% at the V8 stage (eight-leaf stage), 40% at the VT stage (tasseling), and 30% at the R1 stage (silking), significantly enhances grain yield (Ahmed and Patra, 2025). This specific nitrogen application schedule ensures a higher availability of nitrogen during the crop's critical reproductive stages, particularly the grain-filling phase. By supplying a substantial portion of nitrogen later in the growth cycle, especially at VT and R1 stages, SN5 supports optimal nutrient availability precisely when the plants have the highest demand for nitrogen to support reproductive growth (Chaudhary et al., 2015). This targeted late-season nitrogen side-dressing promotes increased nitrogen uptake by the plants, leading to improved assimilation of not only nitrogen but also other essential soil nutrients. This comprehensive nutrient absorption boosts the physiological processes necessary for robust cob and grain development (DMR, 2008). As a result, SN5 contributes significantly to yield-enhancing traits, ultimately increasing overall grain yield (t ha⁻¹) when compared to other nitrogen management strategies (DMR, 2007a).

In comparison, the SN3 approach (20% nitrogen at basal, 20% at V8, 40% at VT, and 20% at R1) provides a moderate level of nitrogen during the reproductive stages but falls short of the late nitrogen concentration seen in SN5. Consequently, SN3 does not achieve the same level of nitrogen availability at the grain-filling stage, which can limit potential yield benefits. Meanwhile, the SN1 approach (50% nitrogen at basal, 25% at knee height stage, and 25% at VT) applies a large initial dose and smaller doses later, resulting in lower nitrogen availability during the crucial reproductive stages. This leads to comparatively lower nutrient uptake and reduced yield attributes (Ramu and Reddy, 2007).

3.2 Cost of Cultivation (Rs. ha⁻¹)

Cost of cultivation differed significantly as influenced by varying crop geometry during both years of the study. Among different crop geometry, statistically higher cost of cultivation was observed in PG3 (78,081.49 and 80,865.09 Rs. ha⁻¹) followed by PG2 (75,081.49 and 77,565.09 Rs. ha⁻¹) and significantly lowest cost of cultivation was recorded in PG1 (73,681.49 and 76,165.09 Rs. ha⁻¹) respectively during both years of experimentation.

Among varying nitrogen management practices, lowest cost of cultivation was recorded in SN1 (72,886.82 and 75,314.42 Rs. ha⁻¹) and the same cost of cultivation was recorded in the rest of the four nitrogen management treatments (76,296.82 and 78,794.42 Rs. ha⁻¹) respectively during both years of experimentation. The higher cost for SN2 through SN5 reflects the additional labor and management required for multiple split applications compared to the conventional single split approach of SN1.

The PG3 crop geometry (40 x 20 cm, 125,000 plants ha⁻¹) resulted in the highest cost of cultivation in both years. This was expected, as denser planting requires a larger number of seeds and increased labor for sowing, maintenance, and other field operations. Research has shown that higher plant densities often increase input requirements, particularly for labor and seed costs (Amanullah et al., 2017). This aligns with the current results, where higher costs in PG3 reflect its intensified input needs.

The cost of cultivation was lowest in SN1, where nitrogen was applied 50% as basal and 25% each at knee height and VT stages. By applying a large proportion of nitrogen early in the season, SN1 reduced labor and operational costs associated with subsequent applications. However, research indicates that such concentrated applications may lead to nitrogen losses through volatilization or leaching, thereby lowering nitrogen use efficiency (NUE) and potentially affecting yield (Fageria and Baligar, 2018).

3.3 Gross Return (Rs. ha⁻¹)

Gross return differed significantly as influenced by varying crop geometry during both years of the study. Among different crop geometry, statistically higher gross return was observed in PG3 (226,267.9 and 221,563.1 Rs. ha⁻¹) followed by PG2 (174,315.2 and 171,556.5 Rs. ha⁻¹) and significantly lowest values were recorded in PG1 (145,736.7 and 143,451.8 Rs. ha⁻¹) respectively during both years of experimentation. Pooled data of two years shows a similar trend.

Among varying nitrogen management practices, highest gross return was recorded in SN5 (193,258.8 and 187,730.6 Rs. ha⁻¹), followed by SN3 (185,929.8 and 182,480.2 Rs. ha⁻¹), and significantly lowest values were observed in SN1 (173,216.5 and 169,693.3 Rs. ha⁻¹) respectively during both years of experimentation as well as pooled data showed a similar trend.

The enhanced gross returns in PG3 can be attributed to the increased plant population, which typically results in a higher total biomass and grain yield per hectare. According to studies on optimal plant population density, increasing plant density up to a certain threshold maximizes yield by improving light interception and nutrient use efficiency (Mason and Fischer, 2019). However, if density is too high, competition for resources may reduce individual plant yield, though this level was not reached in this experiment.

The split nitrogen application in SN5 aligns closely with the nutrient demand of the crop at key growth stages, enhancing nitrogen uptake and photosynthesis during critical phases (Thapa et al., 2019). Delaying a portion of nitrogen until the VT and R1 stages coincides with peak demand, which can improve grain filling and grain yield and ultimately results in higher gross return.

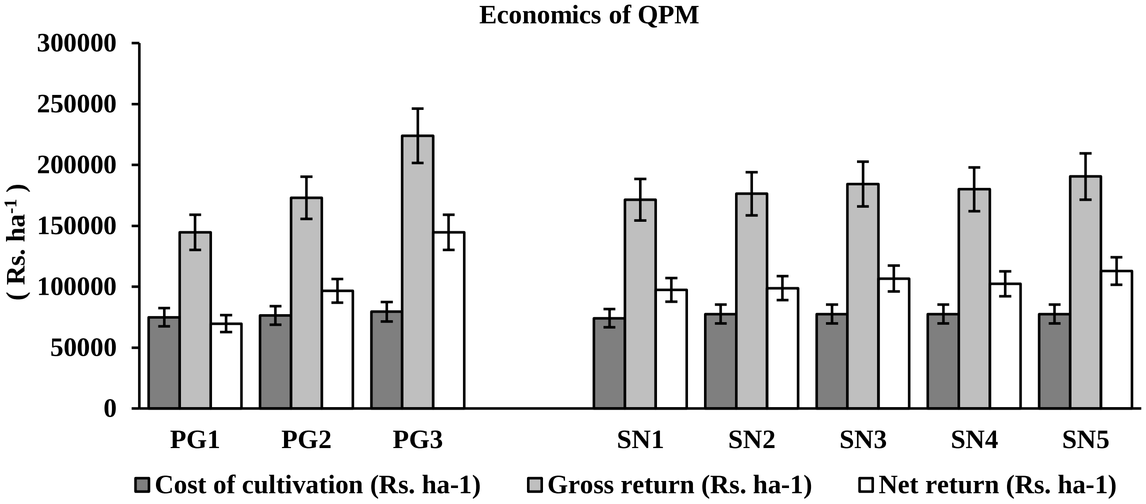

FIGURE 2: Graphical representation of Economics (Rs. ha^{-1}) of QPM as influenced by plant geometry and split nitrogen management.

3.4 Net Return (Rs. ha^{-1})

Net return differed significantly as influenced by varying crop geometry during both years of the study. Among different crop geometry, statistically higher net return was observed in PG3 (148,186.38 and 140,998.04 Rs. ha^{-1}) followed by PG2 (99,233.74 and 93,991.41 Rs. ha^{-1}) and significantly lowest values were recorded in PG1 (72,055.18 and 67,286.66 Rs. ha^{-1}) respectively during both years of experimentation. Pooled data of two years shows a similar trend.

Among varying nitrogen management practices, highest net return was recorded in SN5 (116,961.9 and 108,936.20 Rs. ha^{-1}), followed by SN3 (109,633.0 and 103,685.79 Rs. ha^{-1}), and significantly lowest values were observed in SN1 (100,329.6 and 94,378.91 Rs. ha^{-1}) respectively during both years of experimentation as well as pooled data showed a similar trend.

PG3 recorded the highest net returns, due to the combination of high gross returns and efficient utilization of resources. These findings align with evidence that denser plantings, when combined with adequate nutrient and water management, can achieve higher yields and returns (Islam et al., 2020). PG1, having the lowest density, resulted in smallest net returns, as the limited plant population constrained biomass production and total economic yield.

SN5 achieved the highest net returns. This split application approach allows plants to utilize nitrogen efficiently over time, reducing potential nitrogen losses and leading to greater profitability. Studies have confirmed that delayed applications can minimize nitrogen wastage and increase yield, thus positively impacting net returns (Prasad and Power, 2020).

3.5 Benefit-Cost (B:C) Ratio

B:C ratio differed significantly as influenced by varying crop geometry during both years of the study. Among different crop geometry, statistically higher B:C ratio was observed in PG3 (2.90 and 2.75) followed by PG2 (2.32 and 2.21) and significantly lowest values were recorded in PG1 (1.98 and 1.88) respectively during both years of experimentation. Pooled data of two years shows a similar trend.

Among varying nitrogen management practices, highest B:C ratio was recorded in SN5 (2.54 and 2.37), followed by SN4 (2.43 and 2.31), and significantly lowest values were observed in SN1 (2.31 and 2.22) respectively during both years of experimentation as well as pooled data showed a similar trend.

PG3 recorded the highest B:C ratio, suggesting that, despite higher input costs, the returns on investment were maximized at higher plant densities. The high B:C ratio for PG3 is consistent with findings that optimized plant densities improve economic efficiency by maximizing yield potential and return on resources invested (Kumar and Patel, 2021). The lower B:C ratios in PG1 confirm that suboptimal densities reduce financial returns.

SN5 had the highest B:C ratio, followed by SN3, which also used a staggered approach (20% basal, 20% at V8, 40% at VT, 20% at R1). The higher B:C ratios in SN5 and SN3 indicate that staggered applications not only increase yield but also enhance economic efficiency. Efficient nitrogen timing optimizes the crop's ability to absorb and use nitrogen effectively, as confirmed by studies linking strategic nitrogen applications to improved economic outcomes (Choudhary and Gupta, 2019).

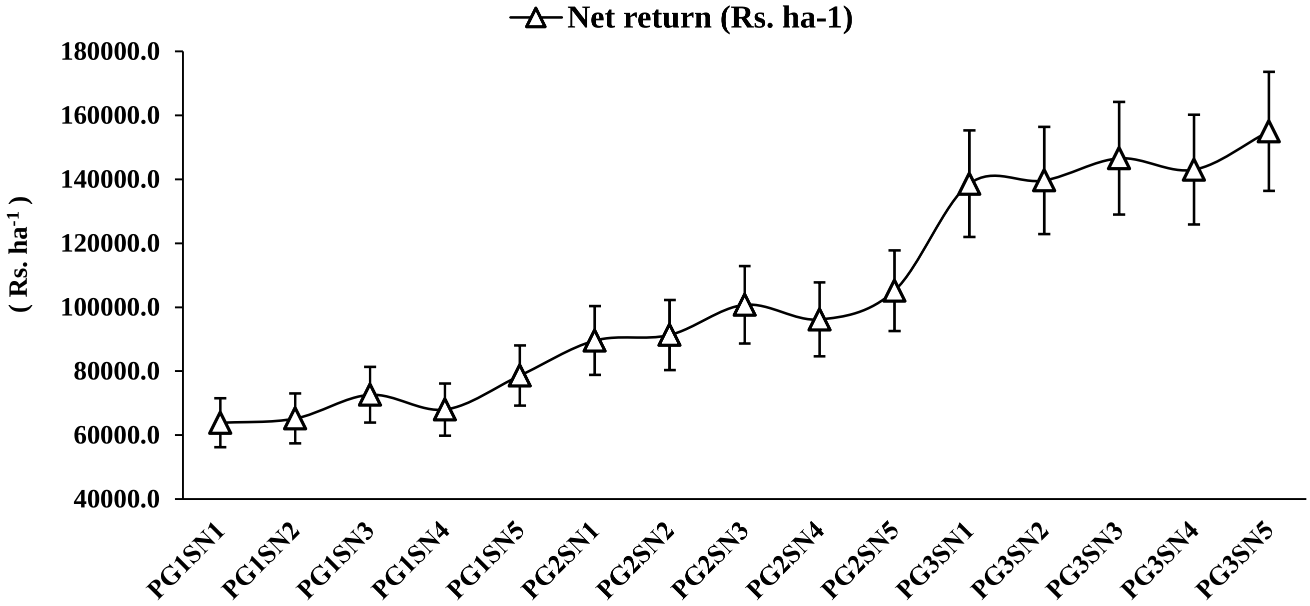

FIGURE 3: Treatment combinations of plant geometry and split nitrogen management on net return (t ha^{-1}) of QPM.

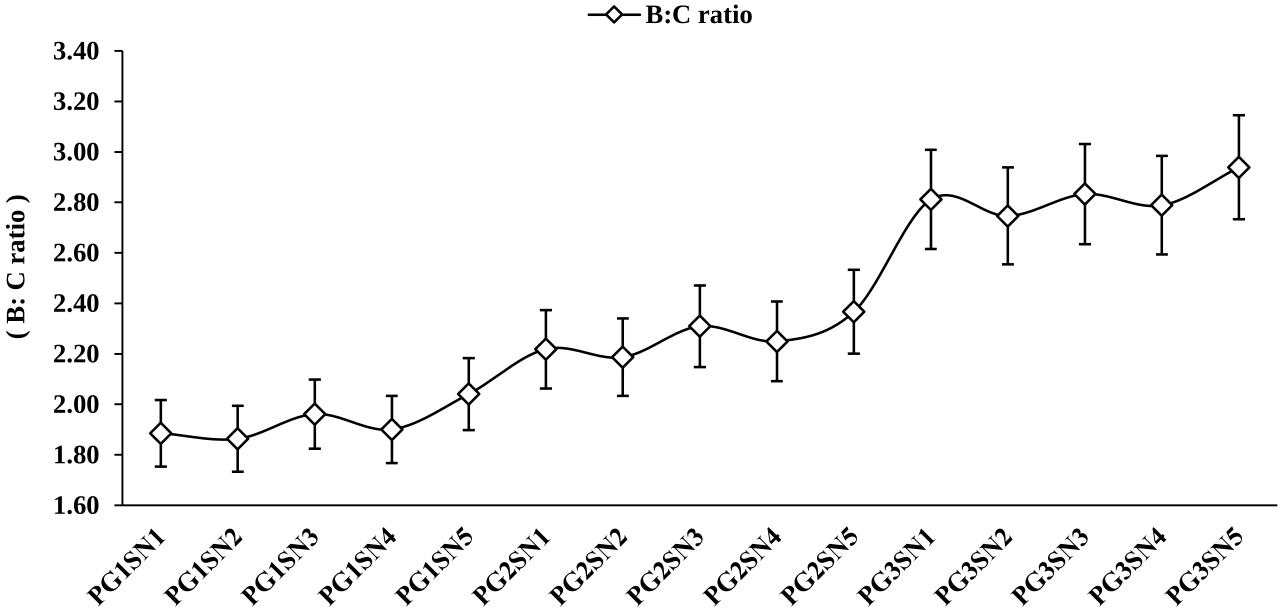

FIGURE 4: Treatment combinations of plant geometry and split nitrogen management on B:C ratio of QPM.

TABLE 1
IMPACT OF PLANT GEOMETRY AND SPLIT NITROGEN MANAGEMENT ON THE ECONOMICS OF QPM

Treatments	Cost of cultivation (Rs. ha^{-1})		Gross return (Rs. ha^{-1})		Net return (Rs. ha^{-1})		B:C ratio	
	2021	2022	2021	2022	2021	2022	2021	2022
Plant geometry								
PG1	73,681.49	76,165.09	1,45,736.70	1,43,451.80	72,055.18	67,286.66	1.98	1.88
PG2	75,081.49	77,565.09	1,74,315.20	1,71,556.50	99,233.74	93,991.41	2.32	2.21
PG3	78,081.49	80,865.09	2,26,267.90	2,21,563.10	1,48,186.38	1,40,998.04	2.9	2.75
Split Nitrogen Management								
SN1	72,886.82	75,314.42	1,73,216.50	1,69,693.30	1,00,329.60	94,378.91	2.37	2.25
SN2	76,296.82	78,794.42	1,77,079.70	1,75,499.60	1,00,782.90	96,705.16	2.31	2.22
SN3	76,296.82	78,794.42	1,85,929.80	1,82,480.20	1,09,633.00	1,03,685.79	2.43	2.31
SN4	76,296.82	78,794.42	1,81,048.20	1,78,881.90	1,04,751.30	1,00,087.45	2.36	2.26
SN5	76,296.82	78,794.42	1,93,258.80	1,87,730.60	1,16,961.90	1,08,936.20	2.54	2.37

Treatment details:

- **Main-plot:** PG1 - 60 x 30 cm (55,555 plants ha^{-1}), PG2 - 50 x 25 cm (80,000 plants ha^{-1}), PG3 - 40 x 20 cm (125,000 plants ha^{-1})
- **Sub-plot:** SN1 - (50% as basal + 25% at knee height stage + 25% VT), SN2 - (25% at basal + 25% at V8 + 25% at VT + 25% at R1), SN3 - (20% at basal + 20% at V8 + 40% at VT + 20% at R1), SN4 - (20% at basal + 20% at V8 + 30% at VT + 30% at R1), SN5 - (10% at basal + 20% at V8 + 40% at VT + 30% at R1)

IV. CONCLUSION

The results clearly indicate that implementing a high-density planting configuration (PG3) alongside a well-timed, staggered nitrogen management strategy (SN5) delivers the most substantial economic benefits. This approach optimizes nitrogen use efficiency by ensuring the nutrient is available during critical growth phases, thereby supporting robust vegetative growth and effective grain filling. As a result, both biomass and grain production are significantly enhanced, leading to superior gross and net returns compared to other treatment combinations. Therefore, the integration of the PG3 crop geometry and SN5 nitrogen management can serve as a highly effective agronomic strategy, offering considerable potential for maximizing profitability in comparable maize-based cropping systems.

CONFLICT OF INTEREST

The authors declared no conflict of interest

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