

Crop geometry and density influence on maize crop

Ayush Ashesh¹ · Harpreet Singh²

Abstract The review critically focuses on maize, one of the most important crops around the world. Different aspects of growing maize at different spacing are covered under this. Maize crop yield directly relates to the plant population and geometry. This article reviews factors affecting the yield of maize and how it gets affected by spacing. Morphology, quality, weed presence, lodging and yield are compared one to one with different populations and arrangement of the crop. Excessive plant population and plant underpopulation both lead to effect in yield. There is need of an optimum plant population where the highest yield along with other parameters will be obtained. With the help of this review, growers and researchers can lead to a better understanding of plant population and geometry influencing in case of high-density production around the world.

Keywords: High density · Crop geometry · Twin row · Paired row · Narrow row · Yield · Quality · Growth

Introduction

In the face of changing climate patterns and a rapidly growing global population, ensuring food supply security with limited arable land has become a critical challenge for the twenty-first century (Gong *et al.*, 2015). Maize is a cereal crop that ranks third in global cereal production after rice and wheat, accounting for approximately 24 per cent of the total cereal production in the world. Maize showed the highest production of 1.2 billion tonnes

in 2021 and the fastest growth over the period (104%) since 2000 (Anonymous, 2021). Food is paramount for human growth and development, yet despite significant efforts to increase food production in recent decades, approximately 1 billion people worldwide still lack access to sufficient food, and an equal number do not meet recommended nutritional standards. The demand for maize, which serves as a vital source of food, fodder, and processed products, is steadily rising. It is projected that by 2025, maize will become the most crucial cereal crop, surpassing rice and wheat in terms of global demand. Indian need of food grain will rise to 42 million tonnes, the order of food will increase with a rapid increase in population despite the on-going health crisis the expected world population by 2050 is 10 billion (Cleland, 2013). In another study estimated that the world population is expected to reach 9.1 billion by 2050, requiring a 70 per cent increase in food production. Developing countries, where hunger and food insecurity are already major issues, will account for most of this growth. In addition to this challenge, urbanization, climate change and the use of land for non-food crops have further compounded the problem. Many countries have prioritized strategies such as agricultural production, land use and population control to tackle this issue (Kumar and Kalita, 2017; Parfitt *et al.*, 2010; Hodges *et al.*, 2011 and Godfray *et al.*, 2010). To address the challenge of increasing food production to meet the demands of a growing global population while facing limited arable land and changing climate conditions, researchers have explored the concept of high planting density for maize. High planting density has been recognized as a promising solution to increase crop yield and meet the nutritional requirements of an expanding population (Sher *et al.*, 2017; Gao *et al.*, 2010). Maize stands out as a particularly sensitive crop when it comes to plant population per unit area, boasting the

✉ Ayush Ashesh: ayushdwivedy@gmail.com

¹Agronomy, ²Agronomist, Punjab Agricultural University, Ludhiana, Punjab, India

highest grain yield potential and thus offering reliability in food production (Vega *et al.*, 2001). Crop geometry, or the arrangement of crops in the field, plays a crucial role in maximizing agricultural productivity. It affects light interception, a key factor in the photosynthesis process and energy production in plants. Additionally, crop spacing impacts both above-ground and below-ground plant structures, particularly when plants compete for space. Optimal plant spacing is essential to achieve the highest yield (Obi, 1991). In the United States, another effective technique for increasing maize yield is twin-row planting. This approach enhances yield without compromising phytochemical variables and reduces competition among rows, allowing for a higher plant population per unit area (Balem *et al.*, 2014). To maximize yield from a given area, achieving the optimum plant population in the field is paramount. This involves an efficient utilization of underground resources and solar energy to promote higher photosynthate production (Thavaprakash *et al.*, 2005). Different plant populations lead to varied microclimates within the crop, ultimately influencing maize yield and quality parameters (Ahmad, 2003). Narrow-row planting, such as twin-row systems, has been shown to boost productivity in maize crops, especially in regions like central Hokkaido, where population densities range from 70,000 to 1,20,000 plants per hectare. The increased productivity stems from a reduction in per-plant space, which compensates for the lower number of grains per plant (Liang *et al.*, 2020). The interaction between plant shape, population, and row arrangements within the crop canopy affects both PAR (Photosynthetically active radiation) interception and crop yield (Stewart *et al.*, 2003). Unlike some other crops, maize does not form tillers, resulting in lower local assimilate availability due to reduced light interception. Understanding how different plant characteristics are affected by plant density is essential for optimizing maize cultivation.

Plant height is a critical morphological feature that increases with higher plant population and significantly correlates with grain yield (Zuber *et al.*, 1957). Early ground cover by the crop canopy enhances light interception, reduces soil moisture loss, and limits weed growth (Williams *et al.*, 1965; Gallo *et al.*, 1985; Ottman and Welch, 1989). The primary objective of increasing the number of plants per unit area is to boost yield, whether in terms of kernel weight or overall dry matter weight. This approach also aims to make crops more

competitive in favourable conditions, as crop yield is closely related to the total solar radiation intercepted (Cox and Cherney, 2001). Additionally, talking about the environmental aspect reducing the distance between plants has been observed to significantly reduce soil loss and increase ear production compared to wider spacing. Severe storms can cause disproportionate soil loss, but close spacing between plants can mitigate this issue. Crops with upright growth and limited tillage practices allowed for higher runoff and soil loss.

The intercropping of groundnut with maize was found to be the most profitable, while also having the least amount of soil loss due to erosion. Maize planted with urd (*Vigna mungo* L.) gave the second-highest net return while also experiencing minimal soil loss from erosion in the case of planting maize and guar (*Cyamopsis tetragonoloba* L.) in alternating strips of 9-meter width, there was minimal runoff (9%) and soil loss of 3.3 Mg ha⁻¹ (Kukul, 1993). Thus, in paired row there is sufficient space for intercrop in between two paired rows which not only control erosion but give additional yield.

Addressing the challenges of food supply security amidst climate change and a burgeoning global population is of utmost importance. As maize emerges as a key player in meeting these demands, it underscores the necessity for sustainable agricultural practices, innovative solutions, and international cooperation to ensure that food production can keep pace with the evolving needs of our world. Optimizing plant population density and crop geometry, particularly through high-density planting and innovative techniques like twin-row systems, holds significant promise in meeting the increasing global demand for maize while making agriculture more efficient and sustainable.

Effect of crop geometry and density on morphology of maize

The dramatic increase in maize yield over the past 50 years is due to the following sources. Better breeding techniques for high-yielding genotypes, better agronomic management practices (Duvick, 2005). On the front of agronomic interventions crop geometry manipulations is the key to higher yield. Crop geometry is one of the most important agronomic interventions to intercept more light and its conversion to chemical energy which further fixes more CO₂. One of the most important principle of

agronomy is harvesting maximum possible solar energy (Reddy and Reddy 2019). It also changes the dynamics of competition between the plants. Spacing not only changes the above parts of the plant but also alters the rhizosphere. Typically, maize plant is grown at a wider spacing which provides crop a heterogeneous environment (Maddonni *et al.*, 2002). Modern-day maize can tolerate a higher plant population due to its resilience against unfavorable environmental conditions created by increased plant to plant competition in the population and produce more yield per unit area under higher planting density. It also reduces the chances of plants without ears and crops falling due to wind. This is due to its physical stature and different phenological achievements, like short anthesis to the silking interval, only a few non-cob stalks and early silking (Duvick *et al.*, 2004; Tollenaar, 1989; Widdicombe and Thelen, 2002).

Root

Plant roots play a vital role in meeting the plant's nutrient, hormonal, and stability needs (Reddy and Reddy, 2019). In the case of maize, the root system comprises a primary root, known as the taproot, which originates from the seed. This taproot gives rise to numerous lateral roots that extensively branch out in the soil. When we examine the impact of planting density on root development, it becomes evident that narrow rows of corn foster the establishment of a superior root system and leaf structure. This, in turn, promotes a more efficient utilization of essential resources such as water, carbon dioxide, and nutrients (Sharratt and McWilliams, 2005). Several factors are influenced by the use of twin-row planting, with root growth and development being a key consideration. Research indicates that when one plant's roots encounter those of another, their growth halts at that point. In the context of twin-row planting, there is ample below-ground space available for root expansion, enhancing soil nutrient uptake. This reduction in intra-row competition ultimately contributes to improved growth, development, and yield (Karlen *et al.*, 1987). Plant roots, especially in maize, are crucial for nutrient uptake and overall plant health. Narrow-row planting, such as twin-row configurations, can enhance root development by minimizing competition between neighboring plants, leading to more efficient resource utilization and ultimately higher yields.

Leaf

Maize (*Zea mays* L.) leaves provide energy for growth and development. During last 75 years, the increase in density do not increase the per plant leaf area but it contributes towards the increase in yield and leaf per unit area (Lambert *et al.*, 2014). Leaves exhibit alternate leaf arrangement, meaning that each leaf arises at a different point on the stem. This arrangement helps maximize light exposure for each leaf. Better leaf structure is there in the case of narrow row corn which efficiently utilizes the different resources needed for essential processes (Sharratt and McWilliams, 2005). At a higher plant population, the production of grains in hybrids is maintained by adapting to the situation by having more upright and shorter leaves. Winter and Ohlrogge (1973) discovered that when the leaf area index (LAI) below 3 or 4, having upright leaves led to a decrease in grain yield. However, when the LAI was high (5 and above), upright leaves resulted in increased grain yield compared to normal leaves. Additionally, Pepper *et al.* (1977) observed that upright and intermediate leaves were more efficient in utilizing intercepted light than horizontal leaves. This increased light interception under upright leaves contributed to higher grain yield, especially when the LAI reached 5.5. Maddonni *et al.* (2001b) found that the angle at which leaves were inserted into the stem increased (from 50.5° to 55.0° for the uppermost stratum) with an increase in plant population, but it did not show any significant response to row spacing. There is a 40 per cent to 60 per cent decrease in leaf area in later growth phases and around a 40 per cent increase in LAI is observed at a higher plant population (Hay and Porter, 2006). Maddonni *et al.* (2001a) had found that maize leaves are versatile and change orientation to fill the empty space around the unit plant in intra row or inter row. The Similar result were obtained by Bruns *et al.* (2012) reported a higher LAI of 6.3 at twin row planting. In high plant population lamina length decreases both in lower and upper phytomers while width increases in lower phytomers and decreases in upper phytomers (Bos *et al.*, 2000 and Song *et al.*, 2016). Increase in plant density an increases shading of leaves and its senescence was also reported by Tetio-Kagho and Gardner (1987) and Hashemi-Dezfouli and Herbert (1992). Reduction in space resulted in more consistent maize yield due synchronous maturing varieties particularly, hybrids, each

plant having a smaller size and reduced LAI and reduced space leads to early season radiation interception (Hoeft *et al.*, 2000).

Flower

The development of a crop depends upon the basis of its growth stages and growth stages are sensitive to abiotic stress. The adaptation of maize for increased production includes early silking, short anthesis to silking interval, prolificacy, few unfilled cobs and barren plants (Duvick *et al.*, 2004). Plant population significantly affects the vegetative stage, days to tasseling, silking and maturity. Other factors that also influences the above things are quantity and time of nitrogen availability to crop (Amanullah *et al.*, 2009 and Ashraf *et al.*, 2016). Under high density planting decaying after emergence rises by 27 per cent (Bavec and Bavec, 2002). One had to replant the seeds at decaying places which increase the time interval between the anthesis and silking which leads to lower grain cob⁻¹ and an increase in the number of barren cobs and plants that cause abortion of kernel (Hashemi-Dezfouliand Herbert, 1992; Lemcoff and Loomis, 1986). In maize, the synchronicity of male and female flower emergence and differentiation of florets can be enhanced by narrow planting, as reported by (Sangoi, 2001). Despite advancements in hybrid technology for high-density planting, proper cultural practices are still necessary to ensure optimal crop growth. A study conducted by Gozubenli *et al.* (2004) found a similar tasseling period of 54.4 days across different planting densities at Mustafa Kemal University. Furthermore, the timing and duration of growth during the silking stage have been shown to affect maize yield potential (Andrade *et al.*, 1999 and Tollenaar *et al.*, 1992). Thus, it is important for farmers to carefully manage their crops during this critical growth stage to maximize the number and size of kernels produced per ear. Plant height is a critical morphological feature that tends to increase with higher plant populations and demonstrates a significant correlation with grain yield (Zuber *et al.*, 1957 and Ei-Lakani and Russel, 1971). To optimize resource utilization, planting patterns can be adjusted by reducing inter-row spacing and carefully managing the distance between plants within rows, ensuring minimal competition for essential growth factors like light, nutrients, and water (Li *et al.*, 2015; Sharratt and McWilliams, 2005). Higher plant populations in a

given area have been observed to result in reduced leaf area, decreased leaf sheath size, and a decrease in mass between nodes (Bos *et al.*, 2000). Stem diameter is another characteristic that varies with plant population density, with thicker stems observed in lower populations and thinner stems in higher populations. This phenomenon is closely linked to the risk of lodging, where thinner stems are more susceptible to breakage, particularly when affected by pathogens. In another study it was concluded that increasing plant population tends to result in thinner stalk diameters, rendering them more susceptible to damage (Wilcoxson and Covey, 1963). Stanger and Lauer (2007) found that increased plant density contributes to a decrease in rind strength. While narrow row spacing has been extensively analyzed for its effects on stem strength and thickness, paired row planting configurations with more inter-row spaces have not been as thoroughly investigated in terms of these factors. Interestingly, thinner stems were observed to be 13% more prevalent in a planting density of 1,00,000 plants ha⁻¹ compared to 30,000 plants ha⁻¹, which can potentially increase the risk of lodging (Maddonna *et al.*, 2001a). Plant height, planting patterns, and stem characteristics are intricately linked to plant population density and can significantly impact crop yield and lodging susceptibility. Careful consideration of these factors is essential for optimizing agricultural practices and achieving maximum productivity.

Effect of crop geometry and density on the phenology of maize

The development of a crop is on the basis of growth stages, and growth stages are sensitive to abiotic stress. The adaptation of maize for increased production includes early silking, short anthesis to silking interval, prolificacy, few unfilled cobs and barren plants (Duvick *et al.*, 2004). Plant population significantly affects the vegetative stage, days to tasseling, silking, and maturity. Other factors that also influences the above things are quantity and time of nitrogen availability to crop (Amanullah *et al.*, 2009 and Ashraf *et al.*, 2016). Under high density planting decaying after emergence rises by 27% (Bavec and Bavec, 2002). One has to replant the seeds at decaying places which increases the time interval between anthesis and silking leads to lower grain set per cob and increases the number of barren cobs and plants that cause abortion of

kernel (Hashemi-Dezfouli and Herbert, 1992 and Lemcoff and Loomis, 1986).

Effect of crop geometry and density on quality of maize grain

Maize planted at a closure spacing of 60 x 17 cm has higher protein content (12.1%) compared to 60 x 20 cm, 65 x 20 cm, 75 x 20 cm and 75 x 25 cm spacing (Misra *et al.*, 1994). Randhawa *et al.* (2012) also observed that higher grain starch and protein content under 60 x 35 cm as compared with 60 x 15 cm. In other case having 75 x 20 cm spacing produced grain with a higher protein content of 11.1 per cent than the conventional spacing of 60 x 20 cm having 10.5 per cent protein (Srikanth *et al.*, 2009). The above experiment result suggests that changing row space will affect the protein content and starch composition in grain. The activity of RuBPCase (ribulose-1,5-bisphosphate carboxylase/oxygenase), a crucial enzyme involved in photosynthesis, exhibited an average increase of 6.78 per cent when the nitrogen (N) supply level was raised from N (100 kg ha⁻¹) to N (200 kg ha⁻¹) during both years of the study under high density planting of 90,000 plants ha⁻¹. However, an interesting trend emerged when the N supply level was further increased from N (200 kg ha⁻¹) to N (300 kg ha⁻¹). At this stage, RuBPCase activity showed a decline in activity during different phases of the experiment (Liu *et al.*, 2022).

Effect of crop geometry and density on yield

Achieving high maize crop yields requires an adequate number of plants (Monneveux *et al.*, 2005). And to get this number there are two types of systems. Firstly, by decreasing the space between two rows and secondly by changing patterns like twin row paired. The growth of maize plants during the silking stage is directly linked to grain yield (Andrade *et al.*, 1999 and Tollenaar *et al.*, 1992), and the transfer of materials to the ears is also important (Echarte *et al.*, 2004). Duvick (1977) observed that older hybrids produced higher yield at lower plant population and new hybrids produced more at higher plant population for which, it is developed. Duvick and Cassman (1999) concluded that hybrid under a stress of competition produces higher yield. As the number of plants per unit area increases, so does plant stress which

affects maize yield components. The components consist of the number of ears m⁻² (or ears plant⁻¹), kernels ear⁻¹ (or kernels plant⁻¹), and kernel weight. Plant density significantly affects maize yield (kar *et al.*, 2007), and twin-row planting has been found to increase grain yield compared to conventional planting (Karlen *et al.*, 1987). Twin-row planting involves planting two rows close to each other and another pair a little farther apart, resulting in more equidistant plant spacing in the field. This approach can harness the benefits of close rows without increasing costs (Elmore and Abendroth, 2007 and Karlen *et al.*, 1987). Cox *et al.* (2006) also confirm that double-row planting increases kernel yield in maize. Hybrid varieties are more suitable for experiments aimed at determining the optimum plant population (Testa *et al.*, 2016). According to Maddonni *et al.* (2001a), the yield per unit area depends both on the number of plants in that area and an arrangement of the crop. However, increasing plant population decreases cob length, cob weight, grain weight, number of grains per row, test weight, and stalk area by 10.8, 6, 7.1, 10, 18 and 20 per cent, respectively. Yield can be affected by higher plant populations due to a decrease in the number of ears per plant, number of grains per ear, and kernel weight. When planting density increases, kernel weight becomes more stable than other components (Maddonni *et al.*, 2006; Westgate *et al.*, 1997 and Begna *et al.*, 1997). Kernel weight is affected by the source-sink relationship (Borras and Otegui 2001). Grain yield increases up to 90,000 plants ha⁻¹ and then remains constant up to 1,05,000 plants ha⁻¹ before decreasing (Gozubenli *et al.*, 2004). Porter *et al.* (1997) reported the highest yield at 86,400 or 98,800 plants ha⁻¹ use under optimum climatic conditions, but when limited condition leads to highest yield at a lower population of 74,100 plant ha⁻¹. The highest maize yield obtained at population of 90,000 plants ha⁻¹ (Widdicombe and Thelen, 2002). This shows that types of maize variety and climatic condition of that place decides the potential yield. The increased number of grains per unit area compensates for the reduction in cob length, 1000-grain weight, and other attributes. Misra *et al.* (1994) at Bahraich, UP found that closer spacing at 60 x 17 cm improves yield attributes viz., rows ear⁻¹ (21.0) and the test weight (205.1 g) during winter seasons. They also concluded that 60 x 17 cm spacing is having 32.5 per cent higher yield as compared to 75 x 25 cm spacing. In Maharashtra, under paired row

conditions of 45-75 x 20 cm spacing, higher fresh cob yield of sweet corn is observed. The paired row system increases cob yield by 16.8 per cent over 45 x 20 cm and 14.2 per cent over 60 x 15 cm spacing. This improvement in yield is due to overall improvements in all growth and yield-attributing characters (Bharud *et al.*, 2014). The increase in yield with paired or narrow rows does not depend on the pattern of leaf area, plant leaf size, or larger area to intercept more solar radiation. More space between inter pair rows likely enhances the plant's ability to transform solar radiation into grain yield (Sangoi *et al.*, 2001). Additionally, the decrease in biomass accumulation by plant causes a decrease in photosynthetic rate per plant which can increase plant barrenness (Edmeades and Daynard, 1979) as plant population increases (Maddonna and Otegui, 2004). So, an optimum plant population required so there will be least barrenness and the highest yield.

Effect of crop geometry and density on weed

Reduced weed dry matter was reported under narrow row planting of maize (Forcella *et al.*, 1992). The paired row may have the edge over the single row planting because of the more even plant population. There is no significant difference in weed biomass and weed population between single and paired rows (Nelson, 2007). He also observed no relation between post-emergent herbicide and row width. Teasdale (1995) and Johnson *et al.* (1998) suggested that a single post-emergence herbicide with integrated weed management may efficiently control weeds in the case of a twin-row where there is more interception of sunlight in the early phase of the crop, also the canopy closure is one week early in case of 38cm row spacing as compared to 76 cm row spacing and total weed cover were 44 and 69 per cent for 38 and 76 cm row spacing, respectively. There is suppression of weed density by 9 per cent at narrow row of 55cm (Maqbool *et al.*, 2006). Weed density was suppressed by 11 per cent when row space changed from 90 cm to 45 cm. It is found that two planting arrangements with same number of plants reduced weed seed bank by 34, 26, 20 and 5 per cent for the increased nitrogen rates of 200, 300, 400 and 500 kg ha⁻¹, respectively (Fanadzo *et al.*, 2010b and Hemmati *et al.*, 2011). Acciaresi and Zuluaga (2006) observed spacing at 35 × 35 cm had lower weed dry matter than wider

planting at most critical stages like of flowering and maturity. The narrow row of 45cm is quite effective in reducing weed biomass by 58 per cent as compared with 90 cm (Fanadzo *et al.*, 2010a).

Effect of crop geometry and density on Photosynthetically active radiation (PAR)

As the inter-row space between paired rows widens, it allows for increased penetration of light to reach the unobstructed soil surface (Tollenaar *et al.*, 2006). In situations with lower plant population per unit area, as is often the case with narrow rows, the benefits of higher light interception are somewhat diminished. However, widening the row spacing further enhances the interception of active photosynthetic radiation, especially around the critical silking stage (Maddonna *et al.*, 2006). Twin-row planting configurations have shown to achieve a higher leaf area index (LAI) at anthesis compared to conventional planting geometries (Bruns *et al.*, 2012). This increased LAI makes the plant system more efficient in intercepting photosynthetically active radiation (PAR) and promotes a more even distribution of plants, reducing competition within paired rows (Camp *et al.*, 1985). The improvement in light interception during the silking stage has a direct impact on the grain yield of maize in narrow-row planting (Andrade *et al.*, 2002 and Barbieri *et al.*, 2000). Additionally, Radiation use efficiency (RUE) is influenced by plant density and subsequently affects grain yield. The final grain yield also depends on factors such as the number of kernels per plant and the weight of individual kernels during the grain-filling period. These factors contribute to increased grain yield by facilitating the translocation of more assimilates, particularly during the post-silking stage, relying on the intercepted photosynthetically active radiation (IPAR) and RUE (Borras *et al.*, 2003). At the peak of the leaf area index, the fraction of PAR increased significantly, shifting from 0.95 at plant populations ranging from 30,000 to 45,000 plants ha⁻¹ to 0.60 at populations of 90,000 to 1,20,000 plants ha⁻¹. The cumulative value of intercepted photosynthetically active radiation during the silking stage is notably higher when the plant population exceeds nine plants meter⁻² (Maddonna and Otegui, 2006). Increasing plant population has a positive effect on radiation use efficiency (RUE) and intercepted photosynthetically active radiation (IPAR), both of which influence crop yield.

Table 1. Effect of different spacing and arrangement under high density planting of maize along with region of production

Spacing/Type	Maximum Yield	Remark	Place	Reference
Paired row	Fresh cob yield - 162.64 q/ha	Paired row (45-75 x 20 cm) yield more than conventional row	Maharashtra, India	Bharud <i>et al.</i> (2014)
Conventional	Grain weight -26.04 q/ha	Highest yield at 75 x 22.50 cm 60,000 plants ha ⁻¹	Pakistan	Abuzar <i>et al.</i> (2011)
Twin row	Grain yield -134.11 q/ha	Twin row performed better than conventional method at high density	Brazil	Balem <i>et al.</i> (2014)
Narrow twin row	Grain yield -98.70 q/ha	Highest yield at 10 plants m ⁻²	Japan	Liang <i>et al.</i> (2020)
High density	Grain yield - 169.0 q/ha	Highest yield at 12 plants m ⁻²	Italy	Testa <i>et al.</i> (2016)
High density	Grain yield - 109.73 q/ha	Highest yield reported at 90,000 plants ha ⁻¹	Turkey	Gozubenli <i>et al.</i> (2004)
Conventional	Grain yield - 76.90 q/ha	Highest yield at (60 x 20 cm) 83,333 plants ha ⁻¹	Pakistan	Zamir <i>et al.</i> (2012)
Conventional	Grain yield - 121.50 q/ha	Highest yield at (60 x 20 cm) 83,333 plants ha ⁻¹	Bangladesh	Biswas <i>et al.</i> (2014)
High density	Grain yield - 92.0 q/ha	Highest yield at 87,750 plants ha ⁻¹	China	Du <i>et al.</i> (2021)
High density (simple row)	Grain yield - 116.1 q/ha	Highest yield at 10 plants m ⁻²	Iran	Shakarami <i>et al.</i> (2009)
High density (zigzag row)	Grain yield -123.33 q/ha	Highest yield at 10 plants m ⁻²	Iran	Shakarami <i>et al.</i> (2009)
High density	Grain yield -123.33 q/ha	Highest yield at 12 plants m ⁻²	Argentina	Maddoni <i>et al.</i> (2006)
High density	Grain yield -173.20 q/ha	Highest yield at 1,05,000 plants ha ⁻¹ under subsoiling tillage	China	Yu <i>et al.</i> (2019)

Paired row planting configurations, with their increased inter-row spaces, allowing more light penetration into the lower canopy, hold promise for achieving better results compared to narrow-row planting. Additionally, 75 per cent of leaf nitrogen is involved in the photosynthetic process, according to Evans (1989) study. Studies have shown that maize yields are generally higher in temperate zones compared to tropical zones, primarily due to favorable light interception and temperature conditions (Hainzelin, 1998).

Effect of crop geometry and density on ecology

Through industrialization, urbanization and infrastructure development, agriculture, forestry, grasslands and natural areas are losing a significant amount of land (Sahu and Dash, 2011). Additionally, talking about the environmental aspect reducing the distance between plants has been observed to significantly reduce soil loss and increase ear production compared to wider spacing. Severe storms can cause disproportionate soil loss, but close spacing between plants can mitigate this issue. The runoff/rainfall ratio varies depending on the spacing between plants, ranging from 0.01 to 0.73 for close-spaced maize, 0.01 to 0.83 for wide-spaced maize, and 0.02 to 0.92 for bare soil, with the highest ratio recorded during the most significant storms, as observed in a study by Mohammed

and Gumbs in 1982. When maize was planted with a spacing of 60 x 22.5 cm, it resulted in the least amount of soil loss caused by runoff. Crops with upright growth and limited tillage practices allowed for higher runoff and soil loss. The intercropping of groundnut with maize was found to be the most profitable, while also having the least amount of soil loss due to erosion. Maize planted with urd (*Vigna mungo* L.) gave the second-highest net return while also experiencing minimal soil loss from erosion. In the case of planting maize and guar (*Cyamopsis tetragonoloba* L.) in alternating strips of 9-meter width, there was minimal runoff (9%) and soil loss of 3.3 Mg ha⁻¹ (Kukal, 1993). Thus, in paired row there is sufficient space for an intercrop in between two paired rows which control erosion and also give additional yield.

Effect of crop geometry and density on lodging

Increase in plant per unit area increases biomass and yield, however it also increases the competition for environmental resources among plants. The parameters which gets affected under high density are structure and function of individual maize plants and whole populations affect plant morphogenesis, stalk carbohydrate accumulation, stalk cortex tissue, stalk mechanical strength, root structure and root functioning. Therefore, maize plants become more susceptible to stalk lodging as

plant density increases. Under increased population light intensity penetrates less in the canopy which inhibits photodestruction of auxin. A higher concentration of auxin increases the elongation rate causing the length of internode elongation (Tetio-Kagho and Gardner, 1987). In addition, plant density influences the light quality (ratio of red to far-red) during the early growing season and impacts internode length in the lower canopy (Rajcan *et al.*, 2004). The above fact combined with decrease in diameter of stem and less time for internode thickening reported by Jun *et al.* (2017). Therefore, as plant density increases, the length of the basal internode significantly increases whereas the diameter significantly decreases (Gao *et al.*, 2010 and Novacek *et al.*, 2013).

Effect of crop geometry and density on Water use efficiency (WUE)

Water management in maize is crucial for the productivity of maize and a reduced pollution risk source is needed (Gheysari *et al.*, 2009). The reduction in yield can be mitigated if water is applied in an appropriate way (Di *et al.*, 2008). One of the factors that can affect the direct evaporation of water from the soil surface is the elevation of transpiration (T) levels within a canopy. This increase in transpiration serves to reduce daily moisture loss by creating a more humid environment within the crop canopy (Shuttleworth and Gurney 1990 and Choudhury and Monteith, 1988). The reduction in moisture loss from the soil was reported by (Karlen and Camp, 1985). But also, transpiration increase negates any benefits from improved spacing (Hoeft *et al.*, 2000 and Lyon *et al.*, 2009). The shading provided by a crop canopy has an impact on soil evaporation. When nitrogen is applied, leading to a larger leaf canopy in maize crops, it results in increased transpiration (T) and, consequently, reduced water use efficiency (Cooper *et al.*, 1987 and Ogola *et al.*, 2005). Hence, it is possible that during the early stages of the growing season, the presence of a dense crop canopy may lead to a reduction in Esc (evaporation from the soil surface). Achieving a high plant density shortly after sowing is one method to establish a dense crop canopy. Manipulating plant spacing through the use of ground cover in high-density planting can also influence both Esc and T (transpiration). Therefore, altering plant spacing through high-density planting offers a cost-effective approach to adjust soil surface evaporation in

cultivated fields, ultimately enhancing water efficiency. When planting density was raised, water use efficiency saw a notable 24 per cent improvement when fields were under irrigation. However, under rainfed conditions, the same increase in planting density led to a 17 per cent reduction in water use efficiency. At the highest plant population density, daily moisture loss (Esc) decreased by 4 per cent, while transpiration (T) increased by 9 per cent due to the presence of a more extensive crop leaf canopy. Interestingly, irrigation substantially increased both Esc and T by a significant 41 per cent. Notably, there was no significant interaction observed between population density and water regime on either Esc or T. Furthermore, the boost in leaf area index resulting from higher population density was much more pronounced under irrigation, with a remarkable 78 per cent increase, compared to a more modest 21 per cent increase under rainfed conditions (Sani *et al.*, 2008). The maize wheat system is a good option for the farmers in India as it require lower water, improve soil health and balances water cycle (Jalota and Arora, 2002). Replacing rice with maize is important for the higher productivity potential of maize and its versatility to fit in the modern intensive intercropping.

Effect of crop geometry and density on nutrient content

The more requirement of nutrients in case of maize due to the specifications, like its tall stature and high amount of dry matter accumulation. Increase in plant per unit area will lead to higher amount of nutrient for higher biomass. Du *et al.* (2021) from China reported that two N levels (240 and 204 kg N ha⁻¹) applied to the main plots and three plant densities (67,500, 77,625 and 87,750 plants ha⁻¹) resulted in increasing density by 30 per cent required only 15 per cent more nitrogen ha⁻¹ which further increase partial factor productivity of nitrogen by 24.7 per cent. Under higher population, it was observed that there is an improvement in the uptake of nutrients by plants i.e. nitrogen, phosphorus, copper and iron which was further linked directly to biomass and increased biomass by 81 per cent of the plant (Peng *et al.*, 2019). Ciampitti *et al.* (2013) from Indiana observed the relation between plant density and nitrogen rates, effects the uptake of phosphorus (P), potassium (K) and sulfur (S) in maize. These findings suggested that the uptake of P, K and S

at the silking stage is 47, 100 and 58 per cent respectively. The population density and nitrogen rate is responsible for absolute quantities of P, K and S in the biomass as crop grows, but not linked with particular nutrient ratio.

At nitrogen level of 0 to 375 kg ha⁻¹ and the number of plants 6 to 11 per m², the average accumulation of 232 kg N ha⁻¹ in biomass was observed at the yield level of 12,000 kg ha⁻¹ with a net harvest index of 64 per cent. Also, lower dose of N content gram plant⁻¹ at pre-silking, maturity and post-silking stage were observed in the case of high density at 90,000 plant ha⁻¹ as compared to the low density at 60,000 plants ha⁻¹ (Setiyono *et al.*, 2010). Both plant density and nitrogen rate determined the above ground N content to Leaf area index (LAI). The ratio decreases with an increase in density and lower nitrogen level. Higher uptake was observed before silking in case of the higher plant population. The aboveground portion mass accumulation was higher in the case of higher plant population and higher N level between R1 and R6 stage (Ciampitti and Vyn, 2011). Bisht *et al.* (2013) from Pantnagar observed higher uptake of N (230.3 kg ha⁻¹), P (56.2 kg ha⁻¹) and K (211.3 kg ha⁻¹) in the case of 1,00,000 plants ha⁻¹. The timing and quantity of nitrogen availability to the crop also influence these factors, as observed by Amanullah *et al.* (2009) and Ashraf *et al.* (2016).

Conclusion

In the face of global challenges such as changing climate patterns and a rapidly growing population, securing our food supply on limited arable land has become a paramount concern. Maize, a crucial source of food, fodder, and processed products, is expected to take center stage in meeting this demand by 2025. To address this challenge, researchers have explored the concept of high-density planting for maize, recognizing its potential to boost crop yield and fulfill nutritional requirements. Crop geometry, including plant spacing and arrangement, plays a pivotal role in maximizing agricultural productivity. High plant density has been associated with increased maize yields, and various planting patterns and techniques, including twin-row planting, have been investigated to enhance productivity while managing competition for essential resources like light, nutrients, and water. Understanding the impact of plant population density on maize's morphological characteristics, such as plant

height, leaf structure, and stem diameter, is essential for optimizing agricultural practices. These factors influence grain yield and susceptibility to lodging, both critical aspects of successful maize cultivation. Additionally, crop geometry affects various ecological aspects, including soil erosion control and ecological balance. Narrow-row planting and intercropping between paired rows have been shown to reduce soil erosion, making these practices not only productive but also environmentally sustainable. Moreover, optimizing plant population density and crop geometry significantly influences photosynthetically active radiation (PAR) interception and radiation use efficiency (RUE), which are essential for grain yield. In conclusion, the future of maize cultivation lies in innovative practices that maximize plant density, crop geometry, and ecological sustainability. By harnessing these techniques, we can address the global challenge of increasing food production while minimizing the impact on the environment and ensuring food security for a growing world population.

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