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OPINION PAPER

Enhancing state-wide corn (*Zea mays*) productivity by bridging the yield gap between top and average farmers in India

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Abstract Maize is a versatile crop serves multiple purposes which providing both food and feed to humans and livestock. It is also a critical source of starch for various industrial applications. In recent years, maize has gained prominence as a fuel crop, contributing to renewable energy production through its conversion into biofuels, such as ethanol. The physiological attributes of maize plants, particularly their remarkable efficiency in converting solar energy into carbon compounds via photosynthesis, surpass those of many other plants. For breeders, the flower structure of maize facilitates efficient breeding methodologies, enabling the swift development of new and improved genotypes that enhance maize crop productivity. The Government of India (GoI) has mandated the Indian maize group to support ethanol production, aiming for the ambitious target of E20 blending by 2025-26 (20% ethanol mixed with gasoline). However, meeting this increased demand poses a significant challenge for the scientific community. To meet the additional demand, India needs an extra 18-20 million metric tonnes (MMT) of maize over the traditional demand for feed and industry which estimated 42 MMT by 2030. To address these challenges comprehensively, the scientific community must collaborate on both immediate and long-term strategies. In the short term, empowering farmers by disseminating best practices, providing access to improved seeds, and optimizing cultivation techniques can elevate the productivity of a larger number of farmers to match the best-performing farmers in the region. This could be made possible by disseminating best practices, providing access to improved seeds, and optimizing cultivation techniques, the productivity across the board. As a long-term strategy, breeding climate-smart corn hybrids that prioritize traits such as climate resilience, high ethanol recovery, disease resistance, and yield stability offers a sustainable solution. This article covers both immediate and long-term approaches, drawing from practical experiences and research to provide a comprehensive roadmap for enhancing maize productivity and meeting future demands.

Keywords: Bridging · Enhancing · Farmers · Productivity · Yield gap

Introduction

Maize, also known as corn, stands out as a vital cereal crop globally, often called the "cereal queen" due to its impressive productivity and widespread cultivation. Globally, maize yields an average of 5.7 metric tons per hectare (t/ha), contributing significantly to food security and sustenance with an annual production of 1,163.5 million metric tonnes which cultivated in over 160 countries covering approximately 203.5 million hectares in 2022. In India, maize cultivation spans more than 11.2 million hectares, with an impressive production of 37.7 million metric tonnes production during 2023-24. Specialty varieties like baby corn, sweet corn, and popcorn are also gaining popularity. Over the last two decades, aggressive breeding efforts and rapid hybrid replacement have driven growth in maize area, production, and productivity. Despite relying on rainfed conditions for 70% of its cultivation, maize achieves an impressive

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productivity of around 3.5 t/ha, rivaling other cereals in India. This rainfed area faces significant productivity limitations that requires aggressive intervention to further increase the country's average yield.

Maize is grown year-round in India allowing for 2-3 crops annually but this also introduces challenges like increased disease and pest pressure, necessitating vigilant breeding and robust surveillance and deployment of best production practices. High productivity districts such as Uttar Dinajpur, Purnia, Katihar, and Guntur where the productivity exceeding 10.0 t/ha, can serve as learning platforms for areas with lower productivity. Maize has transformed from a mere food crop to a crucial industrial resource, with over 80% of maize production serves purposes such as poultry and animal feed (60-65%), starch, and other industrial uses (18-22%). India's biofuel policy aims to blend 11.7% ethanol with petrol primarily from maize. To achieve targets like E20 by 2025-26 and E30 by 2030, maize production need an additional increase of 18-20 million metric tonnes.

Productivity and *kharif* (wet season) season

Originally, maize was primarily a *kharif* crop, and even today, approximately 70% of maize is grown during the *kharif* season across almost all states in India. The timing of planting depends on the monsoon, leading to early or delayed planting based on monsoon conditions. Even in areas with irrigation facilities, farmers often align their planting with the monsoon due to prevailing high temperature conditions. During the *kharif* season, selecting the right hybrids is crucial, with area-specific hybrids available based on local rainfall patterns and the duration of the rainy season in a particular area or state. While State Agricultural Universities (SAUs) provide recommended technology packages, farmers often develop their own technology packages through trial and error, necessitated by local constraints that impact the effectiveness of standard technology packages. The variations in technology (plant population, panting method, fertilizer allocation, and crop protection) and available products significantly contributes lower overall productivity during the *kharif* season (2.7 t/ha) compared to rabi (5.2 t/ha) (IIMR, 2023). It will be interesting to see how all the components of production technology play a greater role in this low productivity and can be improve by correcting these gaps.

Plant population

The population of plants plays a significant role in the yield farmers. Many farmers believe that using more seeds leads to higher yields, but this can actually be one factors limiting their yield. In some cases, farmers use as much as 25 kg of seeds per hectare, while the recommended is 20 kg per hectare. The interesting factor which gets miss out here is size of the seed and that will be vary and thus, seed weight can be misleading attributes to have recommended plant population. This concept is well-established in the USA and other countries, but it hasn't been widely adopted yet in India. It's very well-known facts that optimum plant population will give the best yield recorded by number of workers (Andrade *et al.,* 2002; Tollenaar *et al.,* 1989; Echarte *et al.,* 2004; Monneveux *et al.,* 2005). Studies have shown that the relationship between seed rate and plant population can be optimized in well-managed fields and favorable climatic conditions. Higher plant densities can lead to increased yield per unit area up to a certain level, as the number of ears harvested per unit area rises accordingly. However, in India during the *kharif* season, this concept needs to be reconsidered as the recommended seed rate does not consistently yield the desired plant population,

During the kharif season, it's important to consider the usable plant population (UPP), which depends on several factors such as hybrid type, leaf angle, seed quality, germinability under stress conditions, and early-stage mortality. Planting typically begins after the onset of rain, which can affect germination due to varying moisture levels in the field and hybrid germinability.

In the *kharif* season, the plant population rarely exceeds 23,000 to 27,000 plants per acre (equivalent to 56,000 to 66,000 plants per hectare). This falls significantly below the optimal plant density required for achieving good yields. Our analysis of the *kharif* season data, particularly from the side-by-side testing (SBS), shows that we observed that the largest plant population achieved on average was 700-800 plants per 10 rows of 20 meters length as compared to required 1000 plants to achieve 66,000 to 75,000 plant per hectare. Addressing this gap is crucial if we aim to narrow the disparity between the best-performing farmers and their counterparts.

Planting pattern

Over time, corn planting patterns in India have shifted from broadcast to line sowing. Nowadays, broadcast planting is rarely practiced, except in hilly or tribal areas. Line sowing, which has continued to evolve, is influenced by factors such as soil type, irrigation systems, and available farm equipment. The recommended row-to-row spacing ranges from 50 to 75 centimeters, with a plant-to-plant spacing of 20 centimeters, resulting in approximately 66,666 to 100,000 plants per hectare.

Understanding these diverse planting patterns is critical as it enables us to develop scientifically informed strategies to achieve optimal plant populations (UPP) based on specific conditions in each area. Evidence supports the effectiveness of paired row systems, where two rows have narrow spacing between them, leading to better yields due to improved sunlight penetration. The paired row planting by distance of 40-50 cm between two rows with a spacing of 80-90 cm between two paired rows. In some areas with narrow spacing requirements due to irrigation limitations, farmers adjust row spacing to enhance water accessibility for plants. For example, in sandy soil, reducing row spacing to 50 centimeters improves water reachability. Another interesting planting pattern emerges in regions where soybean and corn are grown together. Farmers, using soybean planters for corn, adopt row-to-row spacing of 40 to 45 centimeters but increase plant-to-plant spacing from 20 to 35 centimeters. Although limited experiments have been conducted, this approach provides better root space for the plants.

In certain central and southern states where maize and cotton are both cultivated, farmers have developed efficient irrigation systems. Drip irrigation, a permanent fixture in the fields, allows for crop rotation. Cotton is planted with a row-to-row distance of 90 centimeters, and farmers adapt paired rowing for corn with spacings of 35-35-90-35-35 centimeters (230 cm for four rows).

There is ample scope to validate and enhance our scientific understanding of these planting patterns, empowering farmers to align their practices for increased productivity during the *kharif* season with upscaling the best practices. Numerous experiments have been conducted on the paired row system. Bruns *et al.* (2012) reported that pair row planting leads to a higher leaf area index (LAI) at anthesis compared to conventional planting geometries. This increased LAI enhances the overall efficiency of the plant system. Camp *et al*. (1985) concluded that pair row planting improves photosynthetically active radiation (PAR) distribution, resulting in more even plant growth and reduced competition within paired rows. Additionally, Andrade *et al.* (2002) highlighted that pair-row planting enhances light interception during the silking stage, directly impacting maize grain yield compared to narrow-row planting. Furthermore, Barbieri *et al.* (2000) reported that radiation use efficiency (RUE) is influenced by plant density, which subsequently affects grain yield. The effectiveness of paired row planting is also being validated in various agro-ecologies under AICRP on maize where maize planting in 84:50 cm found effective in giving higher yields with better accommodation of intercrop.

Fertilizer

The nutritional requirements of corn plants have been extensively studied, allowing us to determine the optimal levels of nitrogen, phosphorus, and potassium (NPK) needed to produce one kilogram of corn. Numerous experiments conducted worldwide provide insights into the appropriate fertilizer application rates for optimizing yields in specific hybrids. Additionally, understanding the benefits of split nitrogen applications enhances plant efficiency. However, practical implementation is limited to areas with available irrigation systems, where farmers can time their fertilizer applications. In contrast, during the *kharif* season, when over 70% of the planted area relies on rainfed conditions, challenges arise due to the lack of control over irrigation timing. Researchers like Cakir (2004) and Song *et al.* (2019) have highlighted the moisture-sensitive corn that requires different levels of irrigation across growth stages. Claassen and Shaw (1970) have maintained that the severity of the impact on yield is determined by the drought conditions encountered during each growth stage. Moisture stress mainly leads to no supply of nutrients, highlighting the need to reevaluate fertilizer formulations, considering timely and effective utilization by plants. Exploring slow-release fertilizers could enhance field productivity by ensuring continuous nutrient availability (Jat *et al.,* 2019). Furthermore, in regions with limited rainfall duration, finding methods to deliver nutrients to plants even under low moisture conditions becomes crucial. The foliar fertilization in limited moisture availability conditions also a way forward. In summary, there is significant research potential in developing efficient fertilizer strategies for rainfed conditions, where timing depends solely on natural rainfall.

Crop protection

Crop protection is a critical, especially during the stress-prone *kharif* season, when most corn planting takes place after the onset of the monsoon. In many rain-fed areas, stress begins soon after planting and is further compounded at various growth stages.

Weed management

Weed management is crucial during the *kharif* season. Research indicates that potential yield loss in maize due to weeds can range from 18 to 65% by Gharde *et al.* (2018). Further Rani *et al.* (2020) observed and reported that early stage weed stress, which starts from 17 to 29 days after planting, significantly affects the growth parameters and grain yield of maize. The use of the post emergence herbicide can enhance the productivity of maize in the *kharif* season (Jat *et al.,* 2018). Continuous rain soon after planting makes early-stage weed stress difficult to manage and exacerbates weed management challenges. The early post emergence and combination of pre and post emergence herbicide application controls the multiple weed flushes in rainy season and thus, can significantly enhance the productivity (Radheshyam *et al.,* 2021). The farmer often delays fertilizer applications schedule fearing that weeds will adsorb the nutrients. Delayed fertilizer application negatively impacts plant growth and reduces yield. There is a need to develop pre-emergent herbicides that can be used up to the V3 stage to manage early weed stress during the wet season. Additionally, identifying effective post-emergent herbicides is essential to control weeds at later stages.

Insect management

Insects pose another significant problem, potentially damaging up to 80% of crops. The fall armyworm (FAW) *Spodoptera frugiperda* Smith (Lepidoptera: Noctuidae), is considered the most relevant pest in maize in several countries in America, Africa, and Asia (Nagoshi *et al.,* 2019; Suby *et al.,* 2020; Yang *et al.,* 2021; Harrison *et al.,* 2022 and Tay *et al.,* 2023). Farmers in India rely on chemical control, as GM corn is not approved for commercial cultivation. Spraying insecticides in corn fields is challenging, as farmers can only spray until the crop reaches chest height, making post-flowering insect control difficult. It is imperative to identify more efficient insecticides and their formulations with longer-lasting effects to manage insects in the field. The integrated pest management strategy could be a way forward in the present context for sustainable management of the fall armyworm.

Disease management

On the disease front, there are hybrids available with good tolerance to diseases in different regions. For instance, in southern high-elevation areas where northern and southern leaf blight are serious issues, some hybrids can manage these diseases. Similarly, hybrids recommended for stalk rot and ear rot-prone areas are also available. However, the disease resistance programme should be continued with better multiple disease tolerant hybrids.

Conclusion

To enhance productivity during the *kharif* season, focused research is needed to develop area-specific recommendations. This includes selecting appropriate hybrids, appropriate planting geometry, optimizing fertilizer application, improving water management, and enhancing weed and insect management practices. Implementing these recommendations can effectively reduce the gap between the best-performing and average farmers, ultimately increasing productivity.

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