PLANT SCIENCE TODAY
Vol 13(sp9): 1–17
https://doi.org/10.14719/pst.17002

eISSN 2348-1900
OPEN ACCESS

Review Article | Agriculture
2026, Volume 13, Issue sp9, pp. 1-17

Maize-based cropping systems in India: Dynamics, drivers and pathways for climate-resilient sustainable intensification

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Abstract

Maize (*Zea mays* L.) is emerging as one of the most significant cereals in India because of its growing importance in food, feed, fodder and industrial applications. Maize-based cropping systems are evolving toward sustainable intensification, driven by climate variability, resource constraints, technological advances and changing market demands. In this review, the status, dynamics and future prospects of maize cropping systems in India are summarised through a systematic literature review based on the preferred reporting items for systematic reviews and meta-analyses (PRISMA) 2020 framework. A total of 83 studies were selected for qualitative synthesis. Between 1993–94 and 2024–25, maize area, production and productivity increased by 98.1, 352.1 and 124.1 %, respectively. Across the reviewed maize-based systems, conservation agriculture (CA) and diversification were associated with improvements in productivity, water-use efficiency (WUE) and profitability, with reported gains varying across cropping sequences and production environments. This review examines the evolution of major maize-based farming systems across various agro-climatic regions of India, their impact on productivity, resource utilisation efficiency, soil health and agricultural profitability. It also highlights the key drivers of cropping system change, including climate variability, soil and water constraints, improved hybrids, mechanisation, policy support and market demand. Recent developments in CA, integrated nutrient management (INM), precision agriculture and climate smart agriculture are discussed for their potential to enhance resilience and sustainability. Despite substantial advances, constraints such as regional yield gaps, resource degradation, lack of labour and limited market linkages persist. The review identifies certain research gaps and highlights the need for region-specific agronomic and technological interventions, strengthened market linkages and supportive policies to promote climate-resilient, resource-efficient and sustainable maize production in India.

Keywords: agro-climatic regions; conservation agriculture; crop diversification; cropping systems; climate resilience; sustainable intensification; *Zea mays*

Received: 25 July 2026. **Accepted:** 22 September 2026. **Available online:** Version 1.0: 20 November 2026.

Cite this article: Nima JP, Angles S, Karunakaran KR, Dheebakaran Ga, Vasanthi R. Maize-based cropping systems in India: Dynamics, drivers and pathways for climate-resilient sustainable intensification. Plant Science Today. 2026; 13(sp9): 1-17. https://doi.org/10.14719/pst.17002

Introduction

Maize (*Zea mays* L.) is referred to as the "Queen of cereals" and holds significant importance in food, feed and industrial applications, being the third most important cereal after rice and wheat in India (1). Its versatility has led to an increase in its production in recent decades, especially due to its use in the poultry, livestock feed and starch and biofuel industries (2), which has been supported by government policies favoring coarse cereal cultivation and crop diversification (3, 4). Despite these advances, India has lower maize productivity than the global average, with a large national yield gap, highlighting the importance of implementing sustainable production systems and improving resource-use efficiency (RUE) (5).

Maize farming systems are undergoing a dramatic transformation in India because of climate variability, resource scarcity, changing market demand, technological advancements and policy changes. Traditional cereal-based systems are evolving into maize-based systems that include legumes and oilseeds to diversify and increase productivity, RUE and climate resilience (2, 3), while precision farming, conservation agriculture (CA) and integrated nutrient management (INM) are gaining popularity as sustainable technologies to enhance productivity, soil health and environmental sustainability (6, 7).

Although numerous studies have examined specific aspects of maize production in India, including agronomic management, CA, crop diversification, climate resilience, productivity and RUE, the available evidence remains fragmented across individual technologies, cropping systems and regions. Previous studies have generally focused on specific production practices or individual maize-based systems, with limited synthesis of how climatic, biophysical, technological, economic and policy drivers interact to shape cropping-system transitions across different agro-climatic regions of India. In particular, an integrated assessment linking cropping-system dynamics and diversification with productivity, RUE, soil health, economic viability, climate resilience and emerging technological opportunities is limited. Therefore, a comprehensive synthesis is needed to understand the drivers and consequences of maize-based cropping-system transformation and to identify region-specific pathways for sustainable and climate-resilient intensification.

This review therefore synthesises evidence on the status and trends of maize cultivation, the dynamics and diversification of maize-based cropping systems across agro-climatic regions, the major drivers of system change, impacts on productivity and RUE, sustainable management practices, economic dimensions and future technological and breeding opportunities. It further identifies key research gaps and policy priorities for climate-resilient and sustainable intensification of maize production in India.

Methodology

To identify relevant studies on maize cropping systems in India, a systematic literature review was carried out by following the PRISMA 2020 guidelines. Literature was retrieved from the Scopus and Google Scholar databases using combinations of keywords such as “maize" OR “*Zea mays*", "cropping systems", "crop rotation", "crop diversification", "productivity”, "sustainability", "climate resilience" and "India". Scopus and Google Scholar were selected to provide broad coverage of the relevant multidisciplinary and agricultural literature; other databases, including Web of Science, CAB Abstracts, AGRICOLA and ScienceDirect, were not searched because of substantial overlap in coverage with the selected databases and to maintain a focused and manageable search strategy. The search was limited to English-language publications from 2001–2026. Peer-reviewed research articles, review articles and relevant books and institutional reports were also considered.

Studies were eligible for inclusion if they focused on maize production or maize-based cropping systems in India; addressed one or more objectives of the review, including cropping-system dynamics and diversification, productivity, RUE, sustainability, climate resilience, economic aspects or management practices; and provided sufficient information for qualitative synthesis. Studies were excluded if they were unrelated to maize or maize-based cropping systems, were conducted outside India, fell outside the scope of the review objectives, lacked sufficient information for synthesis or had unavailable full texts. Duplicate records were removed before screening. Included studies were qualitatively appraised for quality based on publication in a peer-reviewed journal or a recognised institutional or government source and the indexing status of the source journal (e.g., Scopus- or UGC-CARE listed). Studies with substantial methodological ambiguity, such as non-indexed grey literature, were excluded at the full-text stage.

The initial search identified 1081 records (Scopus = 664; Google Scholar = 417). Using publication year, language and document type filters, the number of records reduced to 892. Following the removal of 176 duplicate records, 716 records were screened based on titles and abstracts. Records unrelated to maize, studies conducted outside India, irrelevant topics were excluded. Later, 230 full-text articles were evaluated for eligibility. Full-text articles were excluded if they were not relevant to the review objectives, lacked sufficient data, focused on topics other than maize cropping systems or if the full text was unavailable. Finally, 83 studies fulfilled the inclusion criteria and were included in the qualitative synthesis. The study selection process followed for this systematic review is illustrated in Fig. 1, which summarises the identification, screening, eligibility assessment and final inclusion of studies according to the PRISMA 2020 framework.

A keyword co-occurrence analysis was carried out using VOSviewer version 1.6.21 based on bibliographic data exported from Scopus. Keywords occurring at least twice were included in the analysis and the association-strength normalisation method was used to normalise the co-occurrence links. Fig. 2 represents the keyword co-occurrence network and illustrates the major research themes and their interrelationships in maize-based cropping systems, with node size indicating keyword frequency and link thickness signifying the strength of co-occurrence between keywords. Different colors indicate distinct thematic clusters. The clusters broadly represent research themes related to soil fertility, fertilisers and agronomic management; CA, crop rotation and profitability; water management and crop productivity; sustainable agricultural intensification and water conservation; maize production and climate change; and residue management and sustainable farming systems. The close interconnections among these clusters indicate that research on maize-based cropping systems increasingly integrates productivity, RUE, soil and nutrient management, conservation practices, water management, sustainability and climate resilience.

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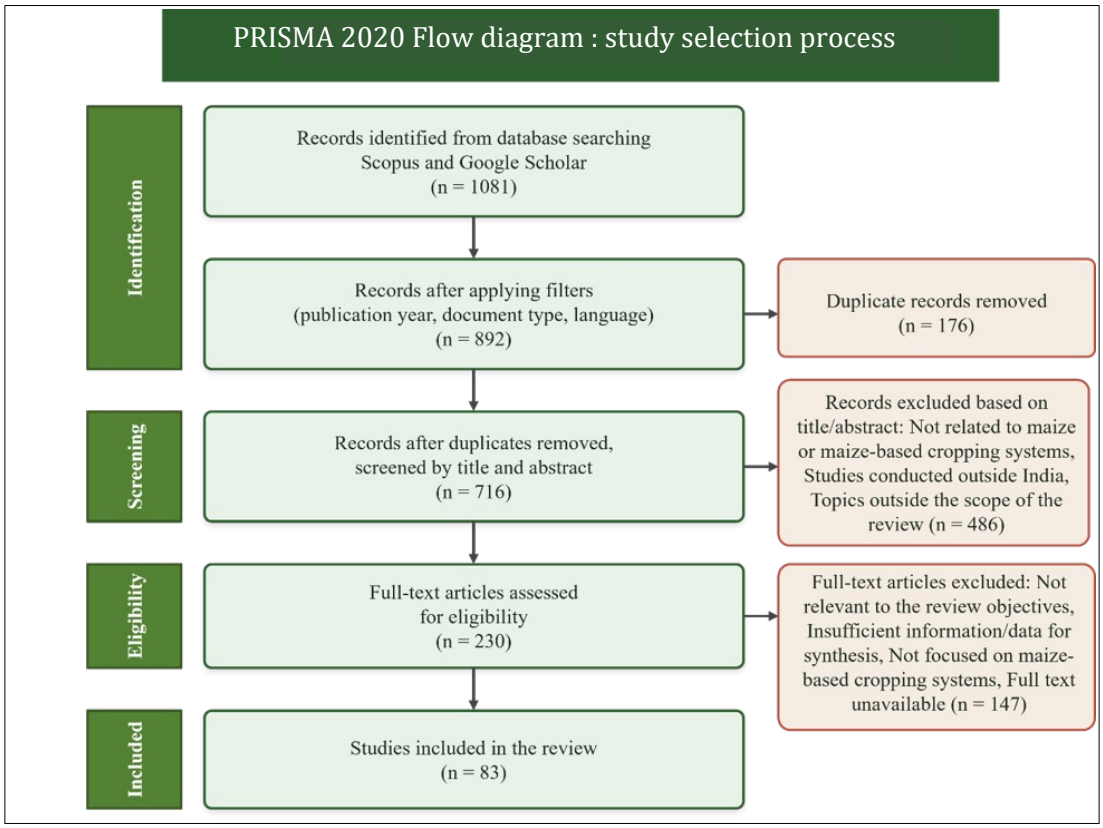


Fig. 1. Preferred reporting items for systematic reviews and meta-analyses (PRISMA) 2020 flow chart depicting the literature search process and study selection procedure.

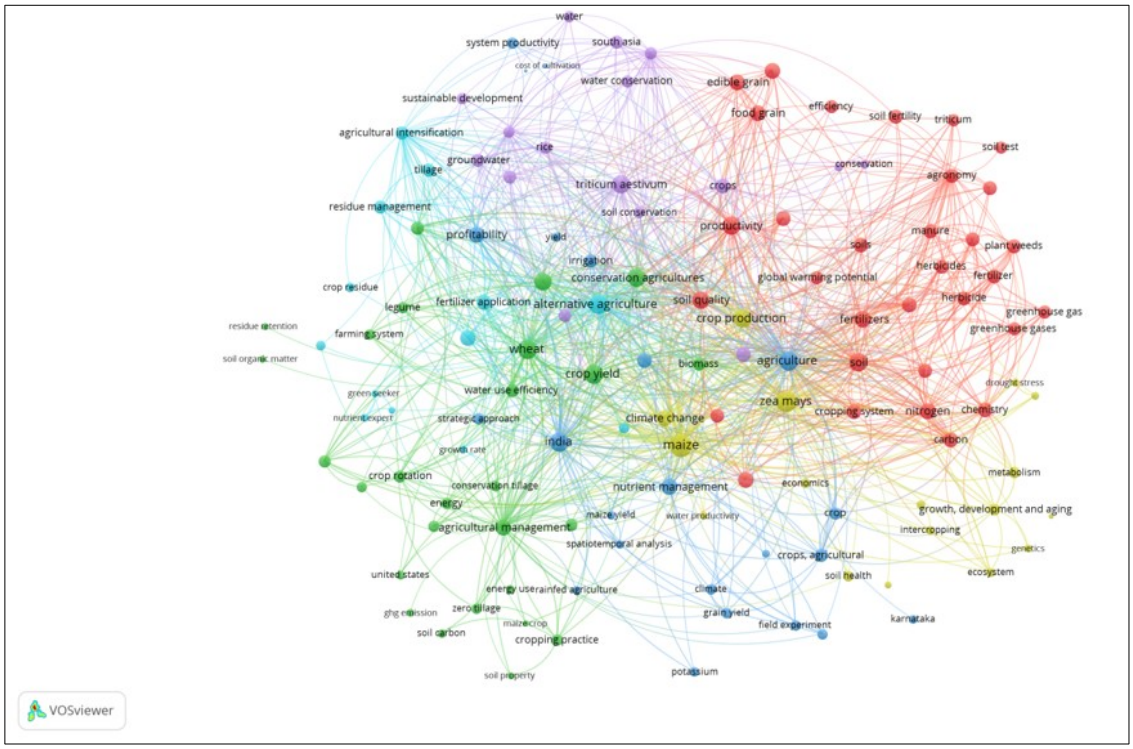


Fig. 2. Network visualisation of keyword co-occurrence. Source : Generated using VOSviewer software.

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Status and trends of maize cultivation in India

In India, maize production is predominantly seasonal with 85 % of the area being cultivated under kharif (south-west monsoon, July–October) cultivation which depends primarily on rainfall and areas with assured irrigation for rabi and spring/summer maize production for year-round production and intensification of cropping systems (1). The major production states include Karnataka, Maharashtra, Madhya Pradesh, Bihar, Andhra Pradesh, Rajasthan, Telangana and Uttar Pradesh, which have different agro climatic conditions influencing variety selection and management (3). In saturated zones, maize is becoming a more suitable alternative to wheat and paddy due to shifting demand and has become a high value cash crop (4). Conservation agriculture is increasingly associated with maize-based system transformation under environmental and economic constraints (6). Nutrient and water management requirements vary considerably across maize-based systems, including maize-wheat, maize-rice, maize-sesame and maize-pulse systems (7, 8). In the Indo-Gangetic Plains (IGP), where maize-wheat is the dominant crop, intensive tillage and imbalanced nutrient inputs have led to soil physical degradation and reduced productivity, prompting the adoption of zero tillage and permanent bed planting (7).

Maize is no longer merely a cereal crop; it has evolved into a versatile commodity suited for food, feed, fodder and industrial use in India. The swift expansion of the poultry and livestock sectors together with increasing demand from starch, food-processing and bio-based industries, has substantially enhanced the commercial importance of maize. The growing use has led to the introduction of better production technology and diversification of maize-based farming systems, especially in areas where the profitability of traditional cereal systems is declining. Maize is thus known to be playing a growing role not just as a food-security crop, but also as an important contributor to agricultural diversification, rural livelihoods and industrial development in India (3, 4, 9).

The regional variation is also high. Maize is an important monsoon staple food in eastern India, especially Odisha, where large yield gaps exist and interventions for optimum plant population, INM and integrated weed management (IWM) could substantially reduce yield gaps (10). In Gujarat, INM of maize-sesame is achieved by using a combination of organic manures and chemical fertilisers for maintaining soil health and microbial population (11). Precise sowing dates and fertiliser application are important for increasing monsoon-maize productivity under the new climatic shift in Punjab (12). Crop diversification is gaining more significance because it helps to mitigate abiotic and biotic stress, enhance nutrient use efficiency (NUE) and promote nutrient cycling and better soil health by incorporating legumes and oilseeds into maize cropping systems, which disrupts disease and pest cycles and boosts soil fertility through nitrogen (N) fixation (13). Stress-tolerant hybrids in rain-fed, drought-prone agroecologies, precision nutrient management (PNM) and mechanisation are emerging trends transforming maize production (14, 15) and machine learning (ML)-based crop recommendation is beginning to influence decision-making and profitability. Household location, caste and access to credit are also significant barriers to technology adoption and require a policy dimension, in addition to biophysical measures.

As illustrated in Fig. 3, maize area, production and productivity in India showed an overall upward trend between 1993–94 and 2024–25, increasing by 98.1, 352.1 and 124.1 % respectively. Production and productivity recorded compound annual growth rates (CAGRs) of 4.99 and 2.64 % respectively, indicating that productivity gains were the principal driver of production growth. This trend accelerated after 2010, with production CAGR increasing from 3.53 % to 6.57 % and productivity CAGR from 1.47 % to 3.89 %. However, production declined sharply by 15.3 % in both 2002–03 and 2009–10, associated with severe monsoon droughts (16). Following subsequent recoveries, production reached a record 43.4 million tonnes (Mt) in 2024–25. Overall, the trend indicates productivity-led intensification of maize production in India, particularly after 2010, despite recurring drought-related fluctuations.

Changing trends and diversification in maize-based cropping systems

Maize cropping system in India was found to have undergone remarkable changes in the dynamics, as maize can be used as a food, feed and raw material for industries. Maize cultivation in India has expanded considerably, with the cultivated area increasing from 5.89 million hectares (Mha) in Triennium Ending (TE) 1981–82 to 9.19 Mha in TE 2011–12, while production rose from 6.49 Mt–21.00 Mt during the same period (17). This expansion has been driven by the transition from monoculture to integrated, climate-resilient cropping systems that improve RUE and soil health (18).

Concept and evolution of maize cropping systems

In India, maize cultivation has evolved from subsistence to intensification and diversification in line with market demand. Maize is traditionally grown under low-input systems, but increasing demand for grain as livestock fodder and industrial raw material has led to widespread adoption of high-yielding varieties and intensive management (19). In response to the environmental footprint associated with conventional tillage and excessive fertiliser use, there has also been a shift towards CA and INM (20). In eastern India, the intensive conventional tillage has degraded soil quality, while declining potassium (K) availability has emerged as an additional constraint highlighting the need for sustainable tillage practices (21). Maize is also an important rotation crop with legumes and other cereals thereby enhancing biological N fixation and system productivity (22).

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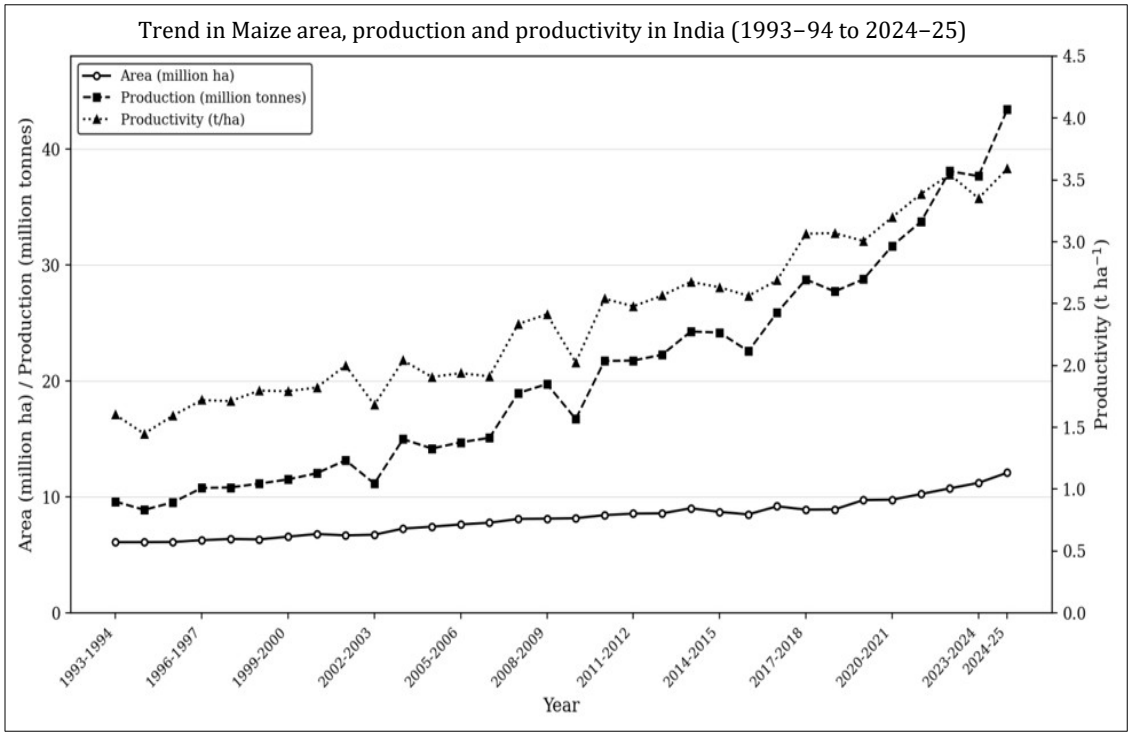


Fig. 3. Trend in maize area, production and productivity in India (1993–94 to 2024–25). Source: Compiled by the authors using data from Ministry of Agriculture and Farmers Welfare, Government of India.

Major maize-based cropping systems

In India, maize-centric cropping system varies across distinct agro-climatic regions in relation to the rainfall and accessibility of water and resources. Kharif maize accounts for 85 % of the total maize area, whereas the rabi and spring maize hold a relatively important position in irrigated areas especially in parts of Northern India such as Punjab (23). Maize is gradually replacing less sustainable cereal systems due to its lower water demand and higher return on investment. The maize-wheat system is the primary cropping sequence in the IGP and central and Northern India, acting as a substitute for the rice-wheat system. The adoption of legumes (mungbean and chickpea) has increased the diversity of the maize–wheat system (24, 25). The rice-maize system is widely practiced in irrigated regions of Andhra Pradesh and Southern India. It has emerged as a water-saving alternative to the rice-rice system, particularly in areas with water constraints (26, 27). Maize is usually cultivated with legumes or mustard in rainfed areas like Odisha and Eastern Himalayas. Comparisons with the maize-fallow system demonstrated that maize-mustard, maize-groundnut and maize-cowpea systems improved soil fertility, crop productivity and farm income (28–30). Other diversified maize-based systems are gaining importance across India. In Bihar, rice-potato + maize has emerged as a highly productive and profitable system (31). In New Delhi, maize-potato-onion and fodder maize + cowpea-wheat-mungbean have shown superior productivity and economic returns (32). In Telangana, okra-maize and maize-onion are among the most profitable maize-based systems (33). The major maize-based cropping systems practiced across different agro-climatic regions of India, together with their characteristics, are summarised in Table 1.

Overall, the major maize-based cropping systems in India include maize-wheat, maize-rice, maize-mustard, maize-legume intercrops and maize-vegetable systems.

Regional differences in maize cropping systems

A significant regional variation in maize cropping exists in India due to agro-ecological diversity. Maize is primarily grown in rotation with wheat in northern IGP; CA technologies (double no-till and permanent raised beds) have positive effects on water productivity and soil physical properties (34). Maize is one of the important food crops of East India, particularly Odisha and West Bengal, where yield gap is observed in the rain-fed plateau regions with poor agricultural practices (10). In eastern India, improved management practices have been identified to improve the profitability of upland rainfed farming, while fuzzy-Multi-criteria evaluation (MCE)-based site suitability analysis is directing maize expansion in novel agroclimatic regions in lower Gangetic West Bengal (29, 35). Natural resource conservation technologies have improved maize productivity and technical efficiency in semi-arid Southern India (36). However, maize diversity is also high in the Eastern Himalayan region where landraces adapted to acid soils and extreme climate are still maintained, but this is being lost as high-yielding hybrids become widespread (37).

Table 1. Regional diversity of major maize-based cropping systems and their key characteristics in India

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Cropping system	Regions/States	Key features and benefits	References
Maize-wheat system	Indo-Gangetic Plains, central and Northern India	Alternative to rice-wheat system; commonly combined with legumes and resource-conserving practices.	(24, 25)
Rice-maize system	Andhra Pradesh, Southern India	Water-saving alternative to rice-rice system, particularly relevant in areas with water constraints.	(26, 27)
Maize-legume/mustard (rainfed)	Odisha, Eastern Himalayas	Maize-mustard, maize-groundnut, maize-cowpea systems show better soil fertility, crop productivity and farm income than maize-fallow	(28–30).
Rice-potato + maize	Bihar	Emerged as a highly productive and profitable diversified system	(31)
Maize-potato-onion; fodder maize + cowpea-wheat-mungbean	New Delhi	Superior productivity and economic returns	(32)
Okra-maize; maize-onion	Telangana	Among the most profitable maize-based systems	(33)

This study suggests that while maize-based systems can have advantages, these are not uniform across regions. Practices that improve water productivity in the irrigated IGP may not provide similar benefits under the rainfed and resource-constrained conditions of Eastern, central and Southern India. This regional variation underscores the importance of assessing different cropping-system options through the lens of local climate, soil, water availability and resource constraints, rather than assuming that a uniform system will be suitable across India.

Cropping system diversification

Cropping system diversification involving maize is increasingly promoted to enhance sustainability. Soil health is adversely impacted by intensive tillage; hence, it is essential to adopt diversified tillage systems for the maintenance of soil health and agro biodiversity (21). Maize-mungbean cropping in semi-arid agro-ecosystems has resulted in better bio-energy, water-use efficiency (WUE) and economic returns (25). Legumes in maize rotations also provide a "rotation effect" by disrupting pest and disease cycles, associated with a more diverse soil microbiome (38). Chemical fertiliser use along with farmyard manure (FYM) preserves fertility and facilitates the activation of microbes in alluvial soils of North-Western India and long-term application with maize-wheat system was observed to increase soil organic carbon (SOC), microbial activity and nutrient status (39). Diversified maize-based systems also deliver valuable ecosystem services in terms of soil biodiversity, nutrient cycling and carbon (C) sequestration. These ecological benefits are important for maintaining soil function and productivity in diversified maize-based systems (38, 39).

The benefits, however, are variable depending on the cropping sequence and production environment. Therefore, diversification is not necessarily better than monocropping, but depends on the complementarity of resource use, length of crop rotation, availability of water and agro-ecological condition

Recent changes and trends in maize cropping systems

New trends in maize cropping are emerging in response to climate variability and advances in precision agriculture. To meet the challenges of climate variability in rain-fed maize, PNM is increasingly being adopted and, in the North-Western IGP, double no-till/permanent raised-bed systems are improving yield, profitability and WUE (34). Natural resource conservation technology has improved productivity and technical efficiency in rainfed Southern India (36). Future prospects include genetic improvement and better agronomic management to reduce yield gaps (19), alongside regional adaptation-strategy assessments to ensure production security for rain-fed maize under future climate uncertainty.

Drivers shaping cropping system change

Maize-based cropping systems in India are shaped by complex interactions among climatic, technological, economic and policy factors, which collectively influence productivity, yield gaps and the sustainability of agricultural production under climate change

Climate variability and weather extremes

Climate variability, particularly drought and heat stress are major factors influencing maize cultivation. Water deficit, especially during critical growth stages, is a major constraint to maize production (14). Recurrent drought and high-temperature stress pose major challenges to maize production in Karnataka, highlighting the need for the adoption of stress-resilient maize hybrids (14). Standardised sowing dates are also necessary to match with the climatic window, as erratic rainfall and extreme temperatures further exert influence (12).

Soil and land resource characteristics

Maize cropping system sustainability depends on soil health. Intensive tillage and imbalanced nutrient management have caused soil degradation and low productivity, especially in low-C calcareous soils, in maize-wheat systems (7). Conservation farming techniques such as no-till cultivation and continuous bed

planting with residue preservation are being followed to enhance soil physical properties whereas partial replacement of N with FYM, vermicompost and neem cake have resulted in better soil microbial counts and N-use efficiency in maize-sesame system (8).

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Irrigation and water availability

Water availability is a critical determinant of maize productivity, as approximately 85 % of the cultivated area is under rainfed kharif conditions (1). Crop diversification is gaining popularity to use water more efficiently and reduce water scarcity (13) and production of rabi/spring maize is growing in the areas where irrigation is guaranteed. Optimised irrigation schedules and precision water-management techniques are essential for maximising yield while conserving water resources (40).

Improved hybrids and varietal development

Drought and heat-tolerant maize hybrids are gaining importance in rain-fed areas to enhance resilience against climate variability (41). Advances in the genetic and molecular understanding of drought-tolerance mechanisms have accelerated the development of drought-tolerant maize cultivars through conventional breeding, genomics-assisted breeding and genome-editing approaches such as clustered regularly interspaced short palindromic repeats and CRISPR-associated proteins (CRISPR/Cas9) (15, 42).

Mechanisation and technological advancement

Specialised equipment aids in conservation tillage methods such as permanent bed planting and no-till farming. Nutrient management tailored to specific sites through fertiliser application is gaining popularity in recent years (7) and ML algorithms are being increasingly used for recommendation of crops and optimising the use of resources. The use of remote sensing, artificial intelligence (AI) and mobile-based guidance is growing and helping farmers with site-specific crop management and timely decisions in digital agriculture. However, wider adoption requires improved digital literacy, extension services and access to affordable technologies for smallholder farmers.

Input availability, labour and profitability

The farmers' cropping decisions are strongly influenced by economic factors, namely the availability of inputs and labour costs as well as profitability. Maize has emerged as a profitable alternative to rice and wheat in regions where the productivity and profitability of traditional cereal systems have plateaued (1, 4).

Government policy and institutional support

The National Food Security Mission (NFSM) has significantly contributed to maize production by promoting improved technologies to meet growing domestic and international demands (3). The support for extension and market infrastructure as well as for research within institutions is still relevant for the promotion of technologies for adaptation to climate change and for increasing sector competitiveness.

Maize-based cropping systems are undergoing transformation in India and the processes of change are mediated by multiple biophysical, technological and socio-economic feedbacks at multiple spatial and temporal scales. Climate variability, depletion of ground water, increasing production cost, etc. are interrelated, compelling farmers to shift from saturated rice-wheat rotation to maize, thereby increasing the demand for stress-resistant maize hybrids, PNM and mechanisation to reduce labour (1, 7, 40). The relative dominance of these drivers varies substantially across agro-ecological zones: the IGP are primarily shaped by groundwater stress, intensive tillage degradation and energy conservation needs (34, 43); the Eastern Plateau and rainfed plains are constrained by large yield gaps, soil K depletion and low input efficiency (10, 21); semi-arid central and Southern India face severe drought and escalating labour costs, necessitating mechanisation and poultry-feed market linkages (1, 14, 44); and the Eastern Himalayas prioritise risk-buffering via adapted landraces and organic legume diversification (30, 37). The drivers of these changes have evolved over time: from rain-fed subsistence and local fodder production (before the 2000s), through to the commercial adoption of maize hybrids to meet rising demand for poultry (2000s–2015), to the current trend towards climate-smart agriculture, digital decision tools and bioethanol blending obligations through national programs (3, 17). Significant agro-ecological synergies are observed with these transitions, such as improvement in land equivalent ratio, biological N fixation and higher net return in maize–legume CA systems (27, 45, 46), but there are also operationally significant trade-offs including shifts in early stage weed flora, costs of multiple residues and competing demands of livestock feed, food security and industrial bioethanol (9, 47, 48). These contrasting outcomes indicate that maize-based system transformation does not produce uniform benefits across regions or sustainability dimensions and that the effectiveness of particular interventions depends on local agro-ecological conditions, resource availability and management practices.

A summary of the major drivers, key challenges, adaptation strategies and supporting references is presented in Table 2.

Impacts on productivity, yield stability and resource-use efficiency

Diversified cropping systems based on maize improve productivity, stabilise yields and optimise RUE compared to traditional cereal monocultures. Conservation agriculture-based integrated crop management (ICM) in maize-wheat systems and maize-wheat-mungbean rotations have improved productivity, WUE, economic returns and soil quality compared with conventional practices (25, 49). The inclusion of legumes and the adoption of CA practices, such as minimum tillage and crop residue retention, improve soil health, NUE and farm profitability while supporting sustainable agricultural intensification (30, 46, 50).

Productivity under different cropping systems

Maize-legume intercropping is effective in land use efficiency due to complementary resource utilisation,

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especially in maize-soybean, maize-green gram and maize-cluster bean cropping systems (45). Likewise, maize-soybean strip intercropping enhances light interception and root resource utilisation, while inclusion of mungbean in annual rotations increases system productivity and farm income (46, 51). The adoption of CA practices such as permanent beds, residue retention and zero tillage results in additional improvements to soil properties, lower establishment expenses and maintenance of higher productivity compared to conventional tillage (21, 27, 52). These benefits are further supported by quantitative evidence from maize-wheat systems, where CA-based maize-wheat management increased SOC by 7.1–14.3 % and microbial biomass C by 10.2–17.3 % compared with conventional tillage (49).

Yield stability and resource-use efficiency

Incorporating legumes helps boost yield stability due to the increased supply of biological nitrogen and the decrease in reliance on synthetic fertilisers (53). Land equivalent ratio (LER) is one of the important parameters used in intercropping systems, which often exceeds 1 compared to sole cropping systems (45). Precision water and nutrient management such as subsurface drip irrigation further supports nitrogen-use efficiency, irrigation water productivity and profitability (54).

In the Indian Himalayas, rotations with high-yielding maize, combined with short-duration legumes or vegetables, increase productivity per year, soil quality and C sequestration (30, 50). In maize-soybean intercropping systems, straw mulching conserves soil moisture and improves WUE under drought-prone conditions (51, 55). Maize-wheat-mungbean systems under CA showed 49.8–66.2 % higher biomass WUE and 8.5–16.1 % lower water use than conventional tillage (25). Recent long-term evidence from the same system further demonstrates the potential of CA to improve water, nutrient and energy-use efficiency (56). In a long-term rice-maize rotation, CA increased system water productivity by 27–68 % and reduced total system water use by 151–423 mm compared with conventional practices (57). In maize-chickpea rotations, CA improved productivity, profitability and soil biological properties compared with conventional tillage (58).

However, soil degradation, reduction of soil organic matter, nutrient deficiency, improper residue management, overuse of fertilisers and climate variability are the constraining factors in adoption (11, 21, 27).

Diversified cropping systems based on maize can improve productivity, yield stability and RUE compared with traditional cereal monocultures, although the magnitude of these benefits varies across cropping sequences and production environments.

The performance of major maize-based cropping systems varies across agro-climatic regions depending on crop sequence and management regimes. Across these systems, the adoption of CA characterised by minimal soil disturbance, permanent raised beds or zero tillage and residue retention consistently enhances agronomic and economic outcomes relative to conventional tillage practices. A comparative summary of reported performance gains across productivity, RUE, profitability and sustainability indicators under CA-based management is presented in Table 3.

The comparison highlights differences among maize-based cropping systems across the reported performance indicators. The magnitude and direction of these indicators vary with cropping sequence, agro-climatic conditions and management practices.

Sustainable and integrated management practices

Maize-based cropping systems represent a pivotal opportunity for sustainable agricultural intensification, national food security, economic stability and environmental resilience. Adoption of CA and ICM represents a promising strategy for improving productivity while reducing environmental footprint (49). This section compiles recent findings on nutrient, water, weed, pest and residue management, emphasising the synergy of a holistic systems approach.

Nutrient management

Integrated nutrient management improves maize productivity by combining inorganic fertilisers with organic sources such as FYM, vermicompost and green manures, thereby enhancing soil fertility, NUE and profitability (8, 59). Nutrient availability is influenced by the carbon to nitrogen (C : N) ratio of organic residues, with legume residues releasing nutrients more rapidly than maize stover (60, 61). Site-specific nutrient management, based on soil testing and optical sensors such as GreenSeeker, improves N-use efficiency while reducing nutrient losses and the environmental footprint (48, 62). Water scarcity is one of the major constraints in maize production especially in IGP (49, 63). Precision irrigation methods like surface and subsurface drip irrigation and fertigation improve water productivity, nutrient absorption and economic gains (64).

Weed management in conservation systems

Managing weed infestation is a major challenge in the first few years after adopting CA, since reduced tillage removes a key form of weed control (48) and the shift from conventional tillage to zero-till can favour perennial and grassy weeds. Integrated weed management integrating cultural, mechanical and chemical controls, such as brown manuring with *Sesbania aculeata* to suppress early weed growth via allelopathy and add soil biomass is necessary for sustainable suppression (48). The combined use of pre-emergence herbicides and threshold-based post-emergence spot spraying effectively suppressed weeds while maintaining crop yield without increasing herbicide use. Crop residue retention further reduced weed emergence by providing physical soil cover (48, 65). The weed community can initially increase in some CA systems but will become

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well controlled in the long-term when using diverse rotation and proper residue management (48, 66).

Table 2. Major drivers influencing maize cropping system dynamics in India

Driver and sub-section	Key challenges / mechanisms	Key interventions and adaptation strategies	References
1. Climate extremes	Water deficit at critical stages; heat/drought stress reducing yield stability.	Shift to stress-tolerant hybrids; optimised and standardised sowing dates.	(12, 14)
2. Soil and land resources	Intensive tillage and imbalanced N-use causing degradation in low-carbon soils.	Conservation agriculture (zero tillage, bed planting); organic N substitution (FYM, vermicompost).	(7, 8)
3. Water availability	High dependence (~85 %) on kharif monsoons; water scarcity.	Crop diversification; precision irrigation scheduling; expansion into irrigated rabi maize.	(1, 13, 40)
4. Hybrid and genetic breeding	Rainfed yield gaps caused by abiotic stress sensitivity.	Breeding drought/heat-resilient cultivars (CRISPR-Cas, wild relative introgressions).	(15, 42)
5. Mechanisation and digital tech	Lack of digital literacy; blanket fertiliser application.	Specialised machinery for CA; site-specific nutrient management (SSNM); AI and remote sensing.	(7)
6. Inputs, labour and economics	High input costs and labour shortages restricting smallholder adoption.	Diversification from saturated rice-wheat systems to higher-margin maize options.	(1, 4)
7. Policy and institutional support	Need for expanded extension services and market infrastructure.	National Food Security Mission (NFSM) incentives; public research and development investment for adaptation.	(3)

AI: artificial intelligence; CA: conservation agriculture; CRISPR-Cas: clustered regularly interspaced short palindromic repeats and CRISPR-associated proteins; FYM: farmyard manure; N: nitrogen.

Table 3. Comparative performance of major maize-based cropping systems under conservation agriculture versus conventional tillage across key agro-ecological indicators in India

Cropping system	Productivity	Resource-use efficiency	Profitability	Sustainability	Reference
Maize-wheat	Maize grain yield: 7.8–21.3 % higher; system yield: 9.5–14.3 % higher	System water productivity: 10.3–17.8 % higher	Additional returns: 24.3–27.4 %; variable production cost: 9.54 % lower	Soil organic carbon: 7.1–14.3 % higher; Microbial biomass carbon: 10.2–17.3 % higher; sustainable yield index: 13.4–18.6 % higher	(49)
Maize-wheat-mungbean	Biomass productivity: 17.2–20.3 % higher	Biomass water use efficiency: 49.8–66.2 % higher; water use: 8.5–16.1 % lower	Net returns: 34.4–39.8 % higher	Higher energy output, energy productivity and energy efficiency	(25)
Rice-maize	Rice-equivalent system productivity: 1.5–38 % higher; maize yield: 6–82 % higher	System water productivity: 27–68 % higher; total system water use reduced by 151–423 mm under conservation agriculture-based systems	Economic profit: US$225–1028 ha^{-1} year^{-1} higher	Lower water use; greater yield stability	(57)
Maize-chickpea	Maize grain-equivalent yield: 13.9–17.6 % higher	System water productivity: 7.5 % higher (zero-till flatbed) and 30.8 % higher (permanent bed)	Net returns: 28.8 % higher (permanent bed) and 24.0 % higher (zero-till flatbed)	Microbial biomass carbon: 8–19 % higher	(58)
Maize-cowpea	Maize yield: no significant difference; additional cowpea yields increased system productivity	System resource productivity increased under diversification	Higher net benefits under the full conservation agriculture package	Minimum tillage + intercropping + residue retention	(29)

Pest and disease management

Climate change affects maize systems by aggravating pest and disease pressure through changes in temperature regime and by increasing the frequency of extreme weather events (67, 68). Integrated pest management (IPM) emphasises economic thresholds and biological and cultural controls before pesticides; CA may have positive or negative impacts on

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arthropods, depending on residue management, with some predators being favored at higher residue levels and some pests at lower levels. Crop rotation and intercropping break pest cycles, rotation of maize with legumes or non-host crops helps to reduce soil-borne pathogen continuity and insect-pest build-up (18, 69); genetic improvement has led to hybrids being resistant to stem borers and leaf blights. Ultimately, IPM success depends on farmer education and locally adapted, environmentally appropriate strategies (70).

Conservation agriculture and residue management

The core principles of CA that are widely recognised globally and essential to sustainable intensification of maize-based systems are minimum tillage, permanent soil cover and crop rotation (47, 71). *In-situ* burning of residue exposes soil surface to erosion, nutrient losses and leads to air pollution in India, whereas keeping residue is beneficial to soil surface protection, soil temperature control and moisture conservation (65). Long-term North-Western India experiments show CA-based residue incorporation increases SOC stocks, aggregate stability, microbial biomass and thermal stability of SOC relative to conventional tillage, indicating greater long-term C-sequestration capacity (49, 61). Conservation agriculture also reduces energy consumption by minimising tillage operations, diesel use and greenhouse gas emissions. However, its adoption may be constrained by limited availability of seeding equipment for residue-intensive fields and temporary reductions in crop establishment (18, 36).

The field-level management practices discussed above – including nutrient and water management, weed management, pest and disease management and CA with residue management, do not operate in isolation, but function together as an integrated agronomic package. Fig. 4 synthesises these specific management components into a single framework, illustrating how their combined implementation under CA and ICM principles builds resilient and sustainable maize-based cropping systems.

Economic viability and market dynamics

Maize-based cropping systems in India are undergoing significant transformation in response to rising input costs, increasing industrial demand and diversification away from traditional rice-wheat systems. Maize provides distinct economic advantages for sustainable intensification, such as reduced production costs when grown under CA and strong value-added potential in industrial use. Operational costs vary widely across states, from about ₹36900 ha^{-1} in Madhya Pradesh to almost ₹62900 ha^{-1} in Tamil Nadu and profitability continues to grow with maize's use as feed, food and industrial raw material (72). Maize intercropping, maize-wheat cropping and multi-crop systems improve system productivity and limit the risk of groundwater depletion and soil degradation in the long term and are more economically sustainable for smallholder farming systems (43, 73).

Cost structure and input-use efficiency

Labour costs are a major cost pressure for small and marginal farmers given low mechanisation in many agro-ecological areas. The cost structure of maize production varies considerably, largely due to differences in labour costs, mechanisation and input intensity. Production in Tamil Nadu can be highly labour-intensive, with high input costs resulting in lower profitability, whereas relatively low labour and input costs in Madhya Pradesh can enhance cost competitiveness (72).

Recent trends indicate a growing emphasis on efficient nutrient and water management in maize cultivation. Practices such as fertigation enhance winter maize productivity and improve input-use efficiency in the Gangetic Plains (40) and CA practices like zero tillage and crop residue retention can reduce input requirements in the long term, as shown by the 29.1 % increase in net income and 17.5 % increase in summer mungbean yields on subsequent crops under maize-based systems (27, 74). However, excessive use of chemical fertilisers is still a concern and a partial replacement of nitrogen in chemical fertilisers with organic manure might maintain the yield while reducing the environmental effects and production cost (59).

Profitability of maize-based cropping systems

Maize-based cropping systems show better profitability than traditional monocultures, especially with legumes or within a CA framework. Maize-wheat represents the third most important cropping system in India with approximately 1.8 Mha, it is a rainfed system and contributes significantly in the national food basket. Economic studies show that replacing rice-wheat with rice-wheat-maize has led to an improvement in factor productivity and profitability due to reduction in environmental stress of continuous cereal cultivation (43) and on-farm participatory research in the IGP indicates that diversification is a strategy for enhancing incomes and reducing environmental stress (73).

In addition to economic advantages, intercropping can help control risks and improve resource utilisation. Intercropping maize with legumes such as chickpea and soybean enhances biological N fixation and complementary resource utilisation, thereby increasing productivity and providing a climate-resilient and economically viable option for smallholder farmers in semi-arid regions (74). Maize-soybean strip intercropping also saves water resources and is superior to sole cropping in this case, resulting in higher land equivalent ratios and farm income (75, 51).

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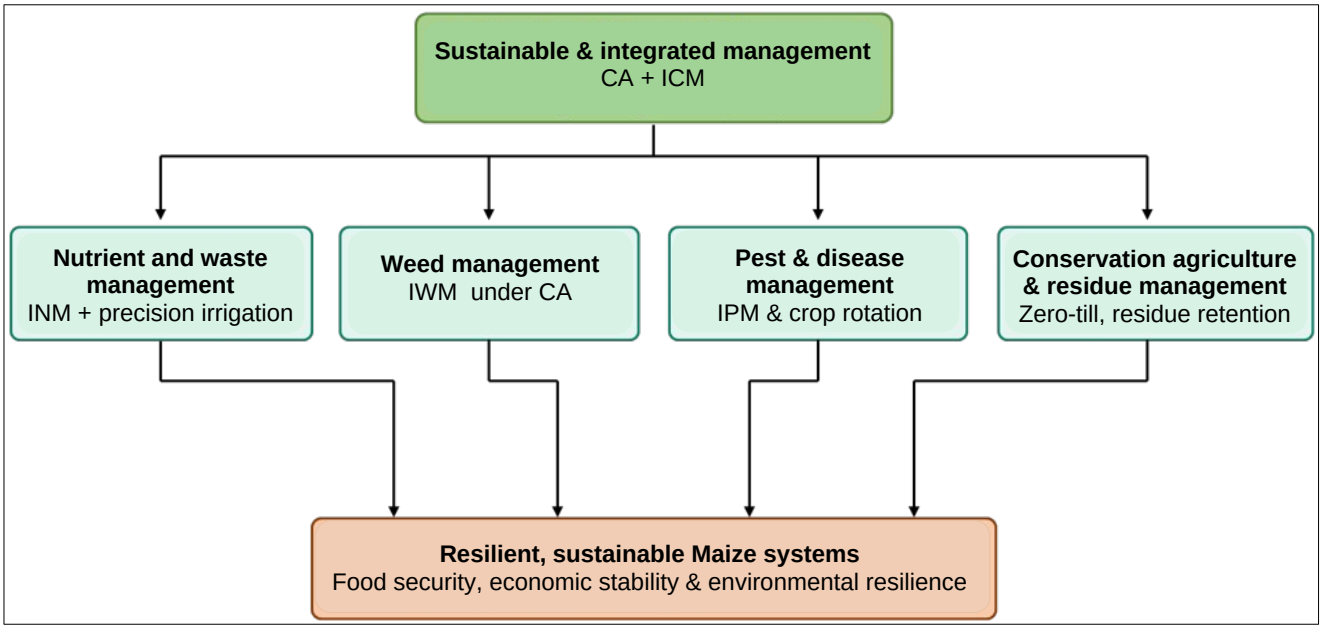


Fig. 4. Field-level integrated agronomic management framework, showing how nutrient, weed, pest and residue management practices combine under conservation agriculture and integrated crop management to build resilient and sustainable maize-based cropping systems. CA : Conservation agriculture; ICM : Integrated crop management; INM : Integrated nutrient management; IWM : Integrated weed management; IPM : Integrated pest management.

Market demand and industrial utilisation

Industrial and feed use is increasingly significant drivers of maize demand in India. The NFSM has focused on maize to meet rising domestic and international demand for feed and industrial raw material while ensuring food security, making maize one of the fastest-growing cash crops (2, 3). Growing demand for niche products like baby corn, sweet corn and popcorn, alongside the expanding poultry industry, has increased value realisation and demand for maize as feed in peri-urban settings (44). Competition between food, feed and fuel uses requires strategic policy decisions balancing food security with industrial development. Bioethanol is a growing industry and value-added maize products are in demand, which is extending market opportunities beyond food and feed. Strengthening market linkages and post-harvest infrastructure will be essential for improving farmers' income and enhancing value addition (9).

Market risks, price volatility and value-chain constraints

Maize-based cropping systems are economically viable not only because of the cost of production and profitability, but also because of market conditions, price stability, policy support and the efficiency of linkages in the value chain. Maize demand from the feed, food processing and industrial sectors creates market opportunities for farmers, but output prices and marketing conditions are also subject to volatility. Studies on maize marketing in India have documented variations in marketing costs, price spreads and marketing efficiency across alternative marketing channels, indicating the importance of market structure and channel selection for farmers' returns (76, 77).

Policy support also influences the economic environment for maize producers. The minimum support price (MSP) for maize increased from ₹2225 per quintal in 2024–25 to ₹2400 per quintal in 2025–26 and was further increased to ₹2410 per quintal for 2026–27 (78–80). However, the economic benefit of MSP depends on farmers' access to procurement and organised markets; therefore, the announced MSP may not necessarily correspond to the price received by every maize farmer.

Marketing arrangements can substantially influence farmers' price realisation. The evidence for maize marketing in Tamil Nadu indicates that there are variations in the number of marketing intermediaries, marketing costs, price spread and marketing efficiency among the marketing channels, with the channels having fewer intermediaries offering higher benefits to producers (76). Similarly, evidence from Davanagere district of Karnataka indicates that Farmer Producer Organizations (FPOs) led maize marketing was associated with higher marketing efficiency and better returns to farmers than conventional marketing channels. Therefore, strengthening of FPOs, collective marketing, storage and post-harvest infrastructure, market information system and linkages with processing industries may help to enhance the efficiency of maize marketing and farmers' access to remunerative markets. In the Karnataka study, FPO-led marketing resulted in higher producer share and improved net returns, demonstrating the potential of institutional marketing arrangements in maize value chains (77).

Thus, the economic sustainability of maize-based cropping systems should be assessed beyond production costs and profitability to include price risk, market access, policy support, marketing efficiency,

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post-harvest infrastructure, institutional linkages and value-chain performance.

Climate change and emerging technologies and future breeding directions

As climate variability increasingly threatens agricultural production, emerging technologies and genetic innovations are expected to play a crucial role in the future of maize production in India, where demand and economic value continue to increase. Conservation agriculture, precision digital technologies and advanced breeding strategies present significant opportunities for climate adaptation and mitigation and can provide farmers with effective tools to decrease the climate vulnerability of agriculture and food security.

Influence of climate change on maize production

The average temperature in India has increased by approximately 0.6 °C over the past century and is projected to rise further in the coming decades, posing significant challenges to agricultural productivity (67). Thermal stress can have a significant impact on maize yields and grain quality (70). Climate-induced changes are also causing pests and diseases to spread their geographical range and irregular rainfall is disrupting planting schedules and also adding to the drought stress in rain-fed systems (68). These challenges are further intensified by declining soil fertility, falling groundwater levels and reduced agricultural profitability, particularly in the IGP (68).

Climate-smart maize production

Climate-smart agriculture (CSA) is at the crossroads of productivity, mitigation and adaptation for maize under climate change. Conservation agriculture-based ICM is one of the pillars of CSA, which saves energy and water and increases economic profit (81). According to field experiments, ICM modules such as zero tillage with raised beds and crop residue retention can perform better in terms of yield maintenance, increase in SOC and enhanced water infiltration and reduction in greenhouse gas (GHG) emissions (71). Use of legumes such as mungbean for N fixation and timing of crops to take advantage of cooler weather during the peak season helps to reduce risk.

Precision agriculture and digital technologies

Precision agriculture is key to mitigating the adverse impacts of climate change on resource utilisation. Site-specific PNM with digital technologies such as GreenSeeker sensors increase NUE and helps provide fertiliser as needed when crop demand changes, while precision irrigation solutions provide maximum WUE in situations with limited groundwater resources (82, 83). Digital technologies offer support in making decisions based on data and signals from the weather and market and mechanisation, such as zero-till seeders and residue management seeders, save on labour, energy and input.

Better hybrids and breeding advances

Productivity and stress resistance have improved significantly in the last 60 years due to genetic improvement; much progress has been made in developing resistance to biotic and abiotic stresses (19). New breeding technologies include drought resistance, heat tolerance and pest resistance in the context of climate smart agriculture and biofortification through provitamin A and micronutrients for nutritional security. Heterosis breeding has driven significant yield gains across agro-climatic conditions and future opportunities include genomic selection and molecular markers to accelerate identification of climate-ready varieties-advances, that combined with better agronomic practices, are crucial for sustaining maize production under a changing climate (19).

Innovative technologies, including AI, drones, remote sensing and internet of things (IoT)-based decision-support systems, are anticipated to enhance resource utilisation and climate adaptability even more. Successful adoption will require affordable technologies, farmer training, robust extension services and supportive institutional policies.

Taken together, all the previous sections show that sustainable maize-based cropping systems rely on the interplay between climatic, agronomic, technological, economic and policy-related factors. These factors affect the diversification of crops, efficiency in use of inputs, productivity, profitability and climate resilience. Fig. 5 presents a conceptual framework linking the major drivers, cropping-system transformation, key outcomes and long-term impacts of sustainable intensification of maize-based cropping systems in India.

Conclusion and Future perspectives

In India, maize cropping systems are experiencing a major transformation due to increased demand, climate change, resource constraints, innovation and the drive to diversify existing cereal-based systems toward maize-based systems. The evidence reviewed indicates that diversified production systems (maize-legume, maize-wheat and maize-rice), using conservation agriculture (CA) and integrated crop management (ICM), can improve productivity, yield stability, resource-use efficiency (RUE), soil health and farm profitability. Regional yield gaps, climate risks, high input costs and labour costs, low mechanisation and inadequate extension services and market linkages, however, continue to limit sustainable intensification. An approach that is region-based and integrated is needed to address these limitations. Research and breeding should focus on drought, heat and pest-tolerant maize hybrids, especially in rainfed regions and extension should be directed towards promoting the adoption of CA, balanced nutrient management, precision irrigation, residue management and suitable crop diversification. Increased availability of custom-hiring and low-cost machinery can reduce the labour and mechanisation constraints and digital

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advisory services can assist farmers in making timely decisions based on weather and crop conditions.

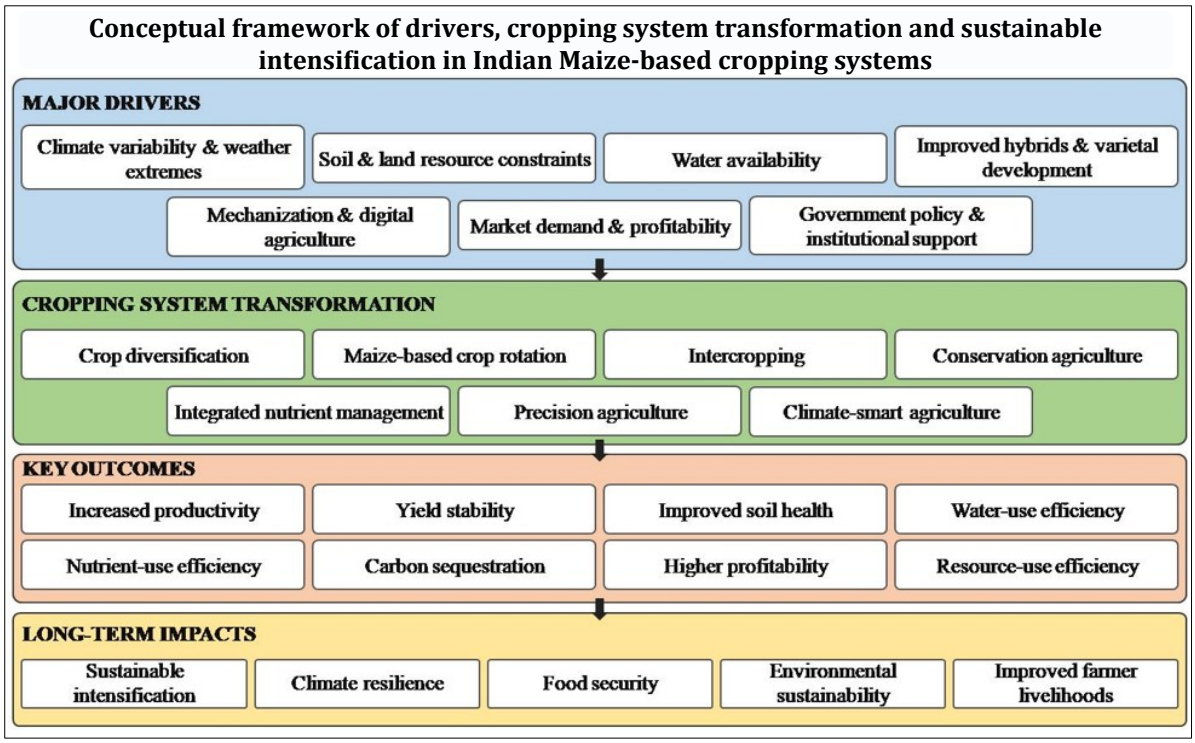


Fig. 5. Conceptual framework summarising the interactions among major drivers, cropping system transformation, key outcomes and long-term impacts for sustainable intensification of maize-based cropping systems in India.

Policy interventions should also prioritise the development of the maize value chain by improving storage conditions, quality certification, farmer producer organisations, marketing systems and linkages with feed and industrial markets. Future research should focus on long-term, regional analysis of maize systems with a focus on productivity, profitability, RUE, soil health, environmental footprint and climate resilience. Increase in maize area or production should not be the only criterion in India, but have to be accompanied with more production with less water, labour, external input or environmental degradation with improved farmers' income and resilience to the future of maize production in India. Hence, synergy in research, extension, technology, infrastructure, markets and policy is essential to make maize systems climate resilient, economically sustainable and environmentally viable.

Authors' contributions

NJP contributed to the conceptualisation of the study, literature search, data extraction and synthesis, visualisation and preparation of the original draft manuscript. SA contributed to supervision, methodology and manuscript review. KRK, GD and RV contributed to manuscript review and editing and provided technical guidance. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly and QuillBot for linguistic refinement and grammar improvement. These tools were used only to enhance the language and readability of the manuscript and did not contribute to scientific interpretation, data analysis, or generation of scientific content. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Peer review: Publisher thanks the Sectional Editor and anonymous reviewers for their contribution to the peer review of this work.

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Publisher information: Plant Science Today is published by Horizon e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.

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https://doi.org/10.14719/pst.17002