



Review article

Area expansion and productivity growth of *Brassica* in Zone-III of India: A comparative analysis across agro-climatic environments

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Abstract

Oilseed Brassica (rapeseed–mustard and related Brassica species) is strategically important to India's edible-oil economy, farm diversification and self-reliance. Rising mustard oil consumption and India's global leadership highlight its critical role in enhancing edible oil self-reliance and food security. Over five decades, India's Brassica sector transformed through varietal, technological and policy interventions, targeting 25.45 million tonnes edible-oil production by 2030–31. This study examines the long-term transformation of Brassica cultivation across AICRP on Rapeseed-Mustard recommendation Zone-III, covering Madhya Pradesh, Rajasthan, Uttar Pradesh, Bihar and Uttarakhand, over 1976–77 to 2025–26. Using secondary data from official agricultural statistics and research databases, the study analyses changes in area, production and productivity across five sub-periods. Compound Annual Growth Rate (CAGR) is used to assess growth trajectories, while the Cuddy–Della Valle Index (CDVI) measures instability after accounting for trend effects. The results reveal substantial structural and spatial transformation in Indian Brassica production. Zone-III increased its share of national Brassica production from 69.47% in 1976–77–1985–86 to 71.06% in 2015–16–2025–26, while its area share declined from 72.09% to 68.08%, indicating stronger productivity gains alongside area expansion. Rajasthan emerged as the major transformation center, with its area and production shares rising sharply, whereas Uttar Pradesh experienced a pronounced decline in both measures. National Brassica area, production and productivity recorded overall CAGRs of 1.54%, 3.79% and 2.22%, respectively, while Zone-III registered 1.45% area and 3.87% production growth. Productivity increased markedly, although substantial inter-state yield differences persisted. Bihar demonstrated production and productivity improvement despite contraction in cultivated area, whereas Uttarakhand showed expansion in area and production within the Western Himalayan region. Instability analysis indicates greater fluctuations in production than area at the national level, with pronounced regional differences. The findings highlight the need for location-specific technologies, quality seed systems, climate-resilient varieties, efficient market linkages, processing infrastructure, farmer producer organizations and stronger local institutions. An integrated productivity–market–institutional strategy is essential to harness Zone-III's potential, strengthen farmer profitability and contribute to India's edible-oil self-reliance and sustainable agricultural development. Such an approach can support inclusive intensification while reducing production risks and strengthening resilient regional value chains.

Keywords: Agro-climatic zone, AICRP Zone-III, compound annual growth rate; cuddy–della valle index, Indian mustard, toria, yellow sarson, yield

Introduction

Agriculture remains an important component of the global economy, with its share in global GDP remaining around 4% since 2000 (FAO Statistics 2022). Within agriculture, the oilseed sector constitutes an important segment because of its contribution to edible-oil supply, food and nutritional security, livestock feed, farm income and industrial uses. Among oilseed crops, oleiferous Brassica species, commonly referred to as rapeseed–mustard, are economically important commodities cultivated across more than 50 countries in Asia, Europe, America and Australia (Prakash and Hinata 1980; Gomez and Prakash

1999). The family Brassicaceae includes several economically important species used as sources of edible oil and food as well as ornamental plants (Shehbaz *et al.*, 2006 and Meyer *et al.*, 2013). The crop group also has considerable potential to meet human, animal and crop requirements while generating beneficial effects for health, environment and the economy (Rabonatahiry *et al.*, 2021). Rapeseed, canola and mustard together constitute the third-largest source of vegetable oil globally.

The historical and geographical importance of Brassica further reinforces its global significance. India has a long history of rapeseed cultivation dating back to 4000 BC,

with subsequent spread to China and Japan (Snowdon *et al.*, 2006 and Daun JK 2011), while the crop was subsequently introduced into Europe and New Zealand, where wild forms of its ancestors were also identified (Zafar *et al.*, 2015 and Shahzadi *et al.*, 2015). Among amphidiploid species, *Brassica juncea* (mustard), derived from *Brassica campestris* L. and *B. nigra* L., is widely cultivated in Asia and occurs in several forms (McNaughton, 1995). Indian mustard is particularly important in warmer environments, especially in India and China (Liu *et al.*, 2022). Comparative studies have demonstrated the agronomic potential of *B. juncea*; Woods *et al.*, (1991) reported higher yield and protein content in mustard than canola under western prairie conditions, while Kjellstrom (1993) observed a higher post-flowering crop growth rate of *B. juncea* than *B. napus* under European conditions. The development of double-low *B. juncea* varieties in Canada further expanded its potential as a canola-type crop (Potts *et al.*, 2003; McVetty *et al.*, 2015). The global Brassica sector is therefore strategically important not only for edible-oil production but also for genetic improvement, crop diversification and sustainable agricultural systems. Heterosis in oilseed Brassica was recognized as early as the 1940s (Sun 1943), while the subsequent introgression of cytoplasmic male sterility from radish through the Ogura system into *B. juncea* strengthened the prospects for hybrid development (Banga and Labana 1984). Multivariate analyses have identified distinct varietal groups associated with geographical centres of origin (Singh *et al.*, 2014), while Myanmar has been identified as an important reservoir of *B. juncea* genetic diversity between the secondary centres of China and India (Wakui *et al.*, 2016). The crop also possesses nutritional and health-related attributes, with leaves and seeds containing glucosinolates and isothiocyanates (Ishida *et al.*, 2014; Shahzadi *et al.*, 2015).

Against this global background, India faces a major edible-oil challenge. About 90 million tons of rapeseed–mustard is produced annually worldwide across 64 countries. India accounts for approximately 22% of global rapeseed–mustard area and about 16% of global production, making it one of the leading producers (FAOSTAT, 2026, STATISTA, 2026; World Rapeseed Production, 2026 and 3rd Advance Estimates 2026, Directorate of Economics and Statistics, Ministry of Agriculture and Farmers Welfare, Government of India). Nevertheless, India's domestic edible-oil supply remains insufficient to meet growing demand, resulting in substantial dependence on imports. Vegetable-oil imports increased from 13.13 million tons in 2020–21 to 16.01 million tons in 2024–25, while the edible-oil import bill

reached Rs. 1.61 lakh crore in 2024–25 and is projected to exceed Rs. 1.75 lakh crore in 2025–26 (The Solvent Extractors' Association of India, 2026). Continued import dependence exposes India to international price volatility, exchange-rate movements and supply disruptions. The import basket is dominated by crude and refined palm oils, soybean oil and sunflower oil (Balaji *et al.*, 2022). Consequently, increasing domestic oilseed production through productivity enhancement, improved technologies and high-yielding, high-oil varieties and hybrids remains central to strengthening edible-oil self-reliance (Kumria R 2023). Mustard oil consumption is North centric and double low-quality mustard enabling to enhance consumption in South India (33rd AGM, AICRP RM 2026). The challenge is further intensified by rising future demand. By 2050, edible-oil demand is expected to increase by 52–76% (NIAP 2025), while India may continue to import about 15–20 million tonnes annually under the behavioristic approach-scenario-I (NITI AYOOG 2024). Oil and fat prices have also shown a rising trend since January 2024 despite negative inflation (Ministry of Statistics and Program Implementation, Government of India and Office of Economic Adviser, Ministry of Commerce and Industry 2025). The structure of India's edible-oil market, comprising approximately 35% raw oil, 55% refined oil and 10% vanaspati, further highlights the importance of a reliable domestic oilseed base (Hegde and Venkattakumar 2010). Thus, India's oilseed challenge is not attributable to inadequate price incentives alone but also reflects structural constraints related to productivity, technology adoption, production risk, processing and market systems.

Within this context, Oilseed Brassica-comprising rapeseed-mustard, toria and related Brassica species-occupies a strategic position in India's edible-oil economy. It contributes substantially to domestic vegetable-oil availability, farm-income diversification and nutritional security. Mustard oil contains appreciable proportions of monounsaturated fatty acids, particularly oleic acid, together with polyunsaturated fatty acids such as linoleic and α -linolenic acids (ICMR-NIN 2024 and FSSAI 2022). Brassica also contributes to sustainable cropping systems beyond India. In Kenya, oilseed mustard has demonstrated potential as a break crop in semi-arid regions by supporting crop diversification and improving cereal-system sustainability (Angus *et al.*, 1999; Mahasi *et al.*, 2008). Similarly, promotion of region-specific, seasonally adapted crops and locally produced agricultural commodities can reduce per-capita water footprints and improve the sustainability of agricultural water use (Jayaram and Mathur 2015). In India, food production used approximately 791.10 BCM of water in

2007-08, with oilseeds accounting for about 9% of agricultural water use, while the economic value of water for rapeseed–mustard varied substantially across states. Over the past five decades, India's Brassica sector has undergone considerable technological and institutional transformation. Varietal improvement, improved production technologies and government programmes—including the Technology Mission on Oilseeds (TMO), National Mission on Oilseeds and Oil Palm (NMOOP), and the National Mission on Edible Oils–Oilseeds (NMEO-OS)—have contributed to improvements in production and productivity. Maharashtra's post-TMO oilseed growth, for example, was associated with substantial productivity gains and increased adoption of soybean and sunflower (Pagire and Nikam 2013). However, the quantitative gains achieved during the TMO period were not sustained at the same rate in the post-TMO period (Jat *et al.*, 2019). This indicates that technological and policy interventions have generated significant progress but that further productivity, institutional and market interventions remain necessary.

Importantly, this transformation has not been spatially uniform. Production has increasingly concentrated in traditional Indian Mustard Dominated Areas (IMDA), particularly Rajasthan, Haryana and Madhya Pradesh, whereas Eastern and North-Eastern India constitute a distinct ecological and socio-economic production system characterized largely by Toria and Yellow Sarson. These regions also possess substantial potential for Brassica expansion. Institutional and market interventions have supported farmer participation in mustard procurement; approximately 5.1 lakh farmers benefited from mustard seed procurement during RMS 2024–25 (CACP 2024), while in Rajasthan, 6.09 lakh MT of mustard seed was procured through 249 centres, benefiting 2.87 lakh farmers during RMS 2019–20 (NAFED, 2019). Yogi *et al.* (2026) reported that the rapeseed–mustard sector generates approximately Rs. 80,000 crore in economic value and over 300 million person-days of employment annually. The sector's sustained production growth contributes significantly to farmers' income, strengthens India's edible oil economy, enhances domestic oilseed availability, and supports the country's goal of edible oil self-reliance. Despite these developments, there remains a critical research gap in understanding the long-term spatial restructuring, differential growth trajectories, productivity dynamics and instability of Brassica cultivation across major production environments within India's AICRP-RM research zones. Existing studies have largely examined national trends, individual states, specific technologies, supply response, productivity or policy interventions. A comparative long-term

assessment integrating area expansion, production growth, productivity enhancement and instability across a geographically diverse research zone is therefore necessary to understand whether India's Brassica transformation has been driven primarily by area expansion, productivity improvement, or changes in regional concentration.

Against this background, Zone-III of the All India Coordinated Research Project on Rapeseed-Mustard (AICRP-RM), coordinated by ICAR–Indian Institute of Rapeseed-Mustard Research (ICAR-IIRMR), Bharatpur, Rajasthan, provides an important analytical setting. The zone encompasses major and contrasting Brassica production environments, including Madhya Pradesh, Rajasthan (Eastern), Uttar Pradesh, Bihar and Uttarakhand. Its geographical diversity, contrasting production systems and changing relative contributions to national Brassica production make it particularly relevant for examining long-term structural transformation. Currently, the varieties of Indian mustard (PM 37, BPM 1825, BPM Q 172); *Toria* (Pant *Toria* 508 and *Azad Chetna*); *Yellow Sarson* (Pant *Sweta*) and *Taramira* (*Krishna Tara*) released for the various states under Zone-III. Accordingly, the present study comparatively analyses changes in area, production, productivity and production stability across major Brassica production regions during 1976–77 to 2025–26. Specifically, it examines regional shifts in Brassica cultivation patterns, identifies differential growth trajectories and productivity dynamics, and assesses instability across production regions. The study further seeks to identify location-specific institutional, technological and market-oriented pathways for sustainable Brassica development and enhanced contribution to India's edible-oil self-reliance.

Methodology

Study area and temporal coverage

The study covers all major Brassica-growing states of India with special emphasis on the agro-ecological/research Zone-III. AICRP-Rapeseed and Mustard Zone-III refers to one of the agro-ecological/research zones under the All India Coordinated Research Project on Rapeseed-Mustard (AICRP-RM), coordinated by the ICAR-Indian Institute of Rapeseed-Mustard Research (ICAR-IIRMR), Bharatpur, Rajasthan. This zoning is specific to rapeseed-mustard research, multilocation trials, variety evaluation, and recommendations. It groups locations with similar growing conditions for Brassica-growing states of India to develop and recommend location-specific varieties and technologies. Based on

classification of Agro-Climatic Zones by the Planning Commission (now NITI Aayog) in 1988-89, states under AICRP Rapeseed and Mustard recommendation Zone-III were clustered into five Agro-Climatic Zones:

- i. CP and H+WP and H-Central Plateau and Hills + parts of Western Plateau and Hills (Madhya Pradesh)
- ii. WDR-Western Dry Region (Rajasthan)
- iii. MUGP-Middle and Upper Gangetic Plains (UP)
- iv. LGP-Lower Gangetic Plain (Bihar)
- v. WHR-Western Himalayan Region (Uttarakhand)

Based on production ecology and dominance of Brassica groups, states were classified into three broad agro-production zones:

- I. Indian Mustard Dominated Area (IMDA): Rajasthan, Haryana, Madhya Pradesh, Uttar Pradesh, Gujarat and other major mustard-producing states.
- II. Toria and Yellow Sarson Dominated Area (TYSDA): Assam, West Bengal, Bihar, Jharkhand, Arunachal Pradesh, Nagaland, Manipur, Meghalaya, Mizoram, Tripura, Odisha and adjoining eastern states.
- III. Brown/Gobhi Sarson Dominated Area (BGSDA): Jammu and Kashmir, Himachal Pradesh, Punjab, Uttarakhand and Himalayan regions.

The IMDA/TYSDA/BGSDA aggregate includes other states outside Zone-III. Hence, the aggregates may differ. The analysis covers a 50-year period from 1976-77 to 2025-26, divided broadly into five decadal phases. This periodisation enables evaluation of technological, institutional and policy-induced changes in AICRP Rapeseed and Mustard recommendation Zone-III. Jha and Sinha (2013), have studied the price of soybeans and rapeseed, based on monthly wholesale prices of these products by using time series data and neural networks methods. Meena *et al.* (2014) forecasted the mustard seed and oil prices in selected Indian markets by using time series and ARIMA model.

Data sources and stakeholder consultation

The study primarily relies on secondary data collected from official sources including Directorate of Economics and Statistics (DES), Ministry of Agriculture and Farmers

Welfare, Government of India; Agricultural Statistics at a Glance; State Agricultural Statistics publications; ICAR research databases; Directorate of Rapeseed-Mustard Research/ICAR-IIRMR datasets; and published research literature and policy documents related to oilseed development. The quantitative database includes state-wise information on area under Brassica cultivation (thousand hectares), production (thousand tons) and productivity (kg ha⁻¹). To supplement secondary analysis, expert consultations were considered from scientists, extension personnel, market stakeholders, seed agencies and progressive farmers involved in Brassica cultivation. Focus Group Discussions (FGDs) were used to understand practical constraints related to access to improved varieties, seed availability, price realization, market infrastructure, processing facilities and institutional support mechanisms. These qualitative insights were integrated with quantitative results to interpret sustainability challenges and development opportunities.

Analytical framework

Compound Annual Growth Rate (CAGR): Temporal growth performance of area, production and productivity was estimated using exponential growth function (Gujarati and Porter, 2009):

$$Y_t = ab^t$$

Taking logarithms:

$$\ln(Y_t) = \ln(a) + t \ln(b)$$

where:

Y_t = area/production/productivity in year t ,

a = constant,

b = regression coefficient.

The CAGR was calculated as:

$$CAGR = (\text{Antilog}(b) - 1) \times 100$$

CAGR analysis was used to identify long-term growth trajectories and regional transformation patterns.

Cuddy-Della Valle Index (CDVI): Instability in area, production and productivity was measured using the Cuddy-Della Valle Index (Cuddy and Della, 1978):

$$CDVI = CV \sqrt{1 - R^2}$$

where:

CV = coefficient of variation,

R^2 = coefficient of determination from trend regression.

The CDVI adjusts simple variability by removing trend effects and provides a more realistic measure of instability.

Lower CDVI values indicate greater stability, whereas higher values represent production uncertainty caused by climatic shocks, market fluctuations, technological limitations or institutional weaknesses. The study combines growth and instability indicators to evaluate sustainability pathways. Regions were compared based on expansion potential, productivity improvement, production stability and institutional support requirements. The analytical framework links quantitative evidence with stakeholder perspectives to identify market access, local institutional mechanisms and value-chain interventions required for sustainable Brassica development in India.

Limitation of the study

This study is based on the secondary data sources and stakeholders' consultations. The classification of IMDA/TYSDA/BGSDA is based on crop concentration and stakeholders' consultations. Hence, interpretation and

use of the findings must be based on the state specific estimates for specific recommendations and policy decisions.

Results and Discussion

Spatial transformation and regional concentration of Brassica cultivation

A marked regional transformation in Brassica cultivation in AICRP on Rapeseed-Mustard recommendation Zone-III is depicted in Fig 1. Indian Mustard Dominated Areas (IMDA) shifted decisively towards the western dry region, with Rajasthan's share rising from 15.26% to 41.54%, while Uttar Pradesh from Middle and Upper Gangetic Plains (MUGP) declined sharply from 47.49% to 13.40%, indicating spatial concentration. Madhya Pradesh from Central Plateau and Hills + parts of Western Plateau and Hills (CP and H+WP and H) showed moderate increase from 7.03% (1976-77 to 1985-86) to 11.83% during

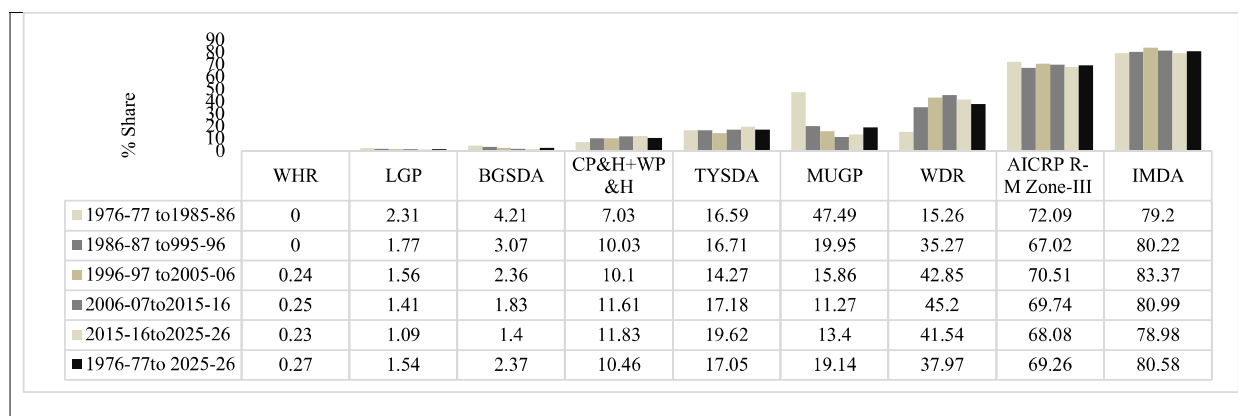


Fig. 1: Share in area of Oilseed Brassica across various agro-climatic zones over the five sub-periods in Zone-III (in %)

Source: Author's Estimates. *The IMDA/TYSDA/BGSDA aggregate includes other states outside Zone-III.

Table 1: Share in production of oilseed Brassica across various agro-climatic zones over the five sub-periods in Zone-III (in %)

Crop group / Agro-Climatic Zone(State)	1976-77 to 1985-86	1986-87 to 1995-96	1996-97 to 2005-06	2006-07 to 2015-16	2015-16 to 2025-26	1976-77 to 2025-26
Indian Mustard Dominated Area (IMDA)	79.53	84.12	87.34	86.49	85.83	85.56
i. Central Plateau and Hills + parts of Western Plateau and Hills (Madhya Pradesh)	6.30	9.53	9.43	10.85	11.80	10.39
ii. Western Dry Region (Rajasthan)	18.19	34.73	43.99	47.61	44.90	41.89
iii. Middle and Upper Gangetic Plains (UP)	42.67	20.14	15.45	10.93	13.29	16.29
Toria and Yellow Sarson Dominated Area (TYSDA)	14.45	13.12	10.56	12.08	13.10	12.53
iv. Lower Gangetic Plain (Bihar)	2.31	1.64	1.34	1.29	0.92	1.30
Brown / Gobhi Sarson Dominated Area (BGSDA)	6.03	2.99	2.10	1.43	1.08	1.99
v. Western Himalayan Region (Uttarakhand)	-	-	0.17	0.17	0.15	0.21
AICRP Rapeseed and Mustard recommendation Zone-III	69.47	66.04	70.32	70.85	71.06	69.99
All India	100.00	100.00	100.00	100.00	100.00	100.00

Source: Author's Estimates. *The IMDA/TYSDA/BGSDA aggregate includes other states outside Zone-III.

2015-16 to 2025-26. In contrast, Bihar from Lower Gangetic Plain (LGP) couldn't retain comparative advantage in *Toria* and *Yellow Sarson* Dominated Areas (TYSDA). However, Uttarakhand from Western Himalayan Region could retain its comparative advantage in *Brown / Gobhi Sarson* Dominated Area (BGSDA). Overall, the area share of AICRP on Rapeseed-Mustard recommendation Zone-III showed moderate decline from 72.09% (1976-77 to 1985-86) to 68.08% during 2015-16 to 2025-26.

Table 1 demonstrates a progressive concentration of Brassica production in the Indian Mustard Dominated Area (IMDA), whose share increased from 79.53% during 1976-77 to 1985-86 to 85.83% during 2015-16 to 2025-26, led by Rajasthan, Haryana and Madhya Pradesh. The sharp decline in Uttar Pradesh's contribution reflects a major geographical restructuring of production. In contrast, Bihar from Lower Gangetic Plain couldn't retain comparative advantage in *Toria* and *Yellow Sarson* Dominated Areas (TYSDA).

However, Uttarakhand from Western Himalayan Region could retain its comparative advantage in *Brown / Gobhi Sarson* Dominated Area (BGSDA). Overall, the production share of AICRP on Rapeseed-Mustard recommendation Zone-III showed moderate increase from 69.47% (1976-77 to 1985-86) to 71.06% during 2015-16 to 2025-26. Within IMDA, Rajasthan emerged as the leading transformation centre, with its area share increasing from 15.26% during 1976-77 to 1985-86 to 41.54% during 2015-16 to 2025-26 and production share rising from 18.19 to 44.90%. In contrast, Uttar Pradesh experienced a significant decline, with area share falling from 47.49 to 13.40% and production share from 42.67 to 13.29%. This shift reflects changing

comparative advantages due to adoption of improved varieties, mechanization, better market connectivity and favourable policy support in western India. In comparison, Eastern and North-Eastern India, represented largely by the *Toria* and *Yellow Sarson* Dominated Area (TYSDA), maintained strategic importance despite a relatively smaller national share. The region's area contribution increased from 16.59 % during 1976-77 to 1985-86 to 19.62% during 2015-16 to 2025-26, while production share declined from 14.45 to 13.10%. Although the regional share remained stable, substantial internal restructuring occurred. The analysis reveals a profound spatial transformation in India's Brassica cultivation in AICRP on Rapeseed-Mustard recommendation Zone-III during 1976-77 to 2025-26, characterized by increasing spatial concentration of production in the Indian Mustard Dominated Area (IMDA), particularly Rajasthan. This indicates that the strengthening of Zone-III's production share was supported by both substantial area expansion and productivity improvement, with productivity gains contributing increasingly to production growth. Table 2 reveals a substantial expansion in Brassica area across India, increasing from 3.79 million ha during 1976-77 to 1985-86 to 7.59 million ha during 2015-16 to 2025-26. While the Indian Mustard Dominated Area (IMDA) remained the principal growth driver, the *Toria* and *Yellow Sarson* Dominated Area (TYSDA) recorded notable shrinkage in Bihar state of the AICRP on Rapeseed-Mustard recommendation Zone III. Conversely, *Brown / Gobhi Sarson* Dominated Area (BGSDA) witnessed persistent contraction with an expansion in the Uttarakhand state of Western Himalayan Region.

The observed spatial redistribution reflects changing

Table 2: Average area under oilseed brassica across various agro-climatic zones over the five sub-periods in Zone III (in thousand hectares)

Crop group / Agro-Climatic Zone(State)	1976-77 to 1985-86	1986-87 to 1995-96	1996-97 to 2005-06	2006-07 to 2015-16	2015-16 to 2025-26	1976-77 to 2025-26
Indian Mustard Dominated Area (IMDA)	3002.08	4457.21	5022.09	5009.13	5990.88	4696.28
i. Central Plateau and Hills + parts of Western Plateau and Hills (Madhya Pradesh)	266.62	557.19	608.19	718.30	897.30	609.52
ii. Western Dry Region (Rajasthan)	578.37	1959.61	2581.21	2795.68	3150.58	2213.09
iii. Middle and Upper Gangetic Plains (UP)	1800.07	1108.45	955.64	697.12	1016.18	1115.49
<i>Toria</i> and <i>Yellow Sarson</i> Dominated Area (TYSDA)	628.79	928.36	859.72	1062.44	1488.16	993.49
iv. Lower Gangetic Plain (Bihar)	87.62	98.54	93.84	87.07	82.75	89.97
<i>Brown / Gobhi Sarson</i> Dominated Area (BGSDA)	159.70	170.39	142.30	113.39	106.14	138.38
v. Western Himalayan Region (Uttarakhand)	-	-	14.43	15.23	17.28	15.83
AICRP Rapeseed and Mustard recommendation Zone-III	2732.68	3723.79	4247.54	4313.41	5164.09	4036.30
All India	3790.57	5555.96	6024.11	6184.96	7585.17	5828.15

Source: Author's Estimates. *The IMDA/TYSDA/BGSDA aggregate includes other states outside Zone-III.

comparative advantages and policy influences. Uttarakhand state performed better with its area expansion from 14.03 thousand hectares to 17.28 thousand hectares and production from 9.87 thousand tonnes to 15.98 thousand tonnes, particularly after 2006–07. Table 3 indicates a fivefold increase in national Brassica production, from 2.17 million tons during 1976–77 to 1985–86 to 10.92 million tons during 2015–16 to 2025–26, reflecting technological advancement and policy support in the AICRP on Rapeseed-Mustard recommendation Zone III too from 1.50 million tons during 1976–77 to 1985–86 to 7.76 million tons during 2015–16 to 2025–26. The Indian Mustard Dominated Area (IMDA) remained the principal production hub, whereas the Toria and Yellow Sarson Dominated Area (TYSDA) more than quadrupled its output, led by remarkable gains in Bihar state of Lower

Gangetic Plain and Uttarakhand state of Western Himalayan Region. Gangwar and Singh (2015) applied the double-log Nerlovian lagged adjustment model, highlighting gradual acreage adjustment toward long-run desired levels based on previous-year acreage and market conditions in Uttar Pradesh state. NABARD (2022) reported relatively low-price responsiveness of rapeseed-mustard supply (elasticity 0.22), indicating limited acreage adjustment to price changes compared with coarse grains and edible oils.

Table 4 highlights substantial productivity gains in the AICRP on Rapeseed-Mustard recommendation Zone III, with the national average yield increasing from 569 kg/ha during 1976–77 to 1985–86 to 1437 kg/ha during 2015–16 to 2025–26, reflecting the combined effects of improved

Table 3: Average production of oilseed brassica across various agro-climatic zones over the five sub-periods in Zone III (in thousand tons)

Crop group / Agro-Climatic Zone(State)	1976-77 to 1985-86	1986-87 to 1995-96	1996-97 to 2005-06	2006-07 to 2015-16	2015-16 to 2025-26	1976-77 to 2025-26
Indian Mustard Dominated Area (IMDA)	1728.83	3999.29	5063.66	6127.85	9375.37	5259.00
i. Central Plateau and Hills + parts of Western Plateau and Hills (Madhya Pradesh)	136.97	452.94	546.50	768.71	1289.21	638.87
ii. Western Dry Region (Rajasthan)	395.45	1651.24	2550.55	3372.99	4904.76	2575.00
iii. Middle and Upper Gangetic Plains (UP)	927.61	957.52	896.04	774.60	1451.69	1001.49
Toria and Yellow Sarson Dominated Area (TYSDA)	314.09	623.73	612.27	855.69	1430.77	770.24
iv. Lower Gangetic Plain (Bihar)	50.17	78.13	77.98	91.63	101.03	79.79
Brown / Gobhi Sarson Dominated Area (BGSDA)	131.01	142.16	121.85	101.19	117.54	122.35
v. Western Himalayan Region (Uttarakhand)	-	-	9.87	11.87	15.98	12.99
AICRP Rapeseed and Mustard recommendation Zone-III	1510.20	3139.83	4076.99	5019.79	7762.66	4301.89
All India	2173.93	4754.13	5797.78	7084.73	10923.69	6146.85

Source: Author's Estimates. *The IMDA/TYSDA/BGSDA aggregate includes other states outside Zone-III.

Table 4: Average yield of oilseed brassica across various agro-climatic zones over the five sub-periods in Zone-III (in kg/ha)

Crop group / Agro-Climatic Zone(State)	1976-77 to 1985-86	1986-87 to 1995-96	1996-97 to 2005-06	2006-07 to 2015-16	2015-16 to 2025-26	1976-77 to 2025-26
Indian Mustard Dominated Area (IMDA)						
i. Central Plateau and Hills + parts of Western Plateau and Hills (Madhya Pradesh)	486.00	803.00	884.50	1065.50	1439.50	935.70
ii. Western Dry Region (Rajasthan)	635.00	840.50	985.30	1205.40	1561.80	1045.60
iii. Middle and Upper Gangetic Plains (UP)	532.20	859.70	950.50	1109.60	1409.50	972.30
Toria and Yellow Sarson Dominated Area (TYSDA)						
iv. Lower Gangetic Plain (Bihar)	573.00	789.00	830.10	1053.00	1219.40	892.90
Brown / Gobhi Sarson Dominated Area (BGSDA)						
v. Western Himalayan Region (Uttarakhand)	-	-	686.17	775.70	917.90	809.73
All India	568.80	847.30	962.10	1144.10	1437.20	991.90

Source: Author's Estimates. *The IMDA/TYSDA/BGSDA aggregate includes other states outside Zone-III.

varieties, technological interventions and policy support. Gross Value of Output (GVO) analysis revealed that rapeseed–mustard generated substantially higher economic returns (Rs. 88,559 ha⁻¹) than safflower (Rs. 16,691 ha⁻¹) among rabi oilseeds (CACRP Report, 2024-25). Within the AICRP on Rapeseed-Mustard recommendation Zone III, significant yield improvements were observed in Toria and Yellow Sarson Dominated Area (TYSDA).

However, the Bihar state of Lower Gangetic Plain and Western Himalayan Region remained a low-productivity region comparatively. Despite expansion in cultivated area, considerable inter-state yield gaps persist, indicating untapped production potential. Bridging these gaps is essential for achieving sustainable and inclusive Brassica development across the Zone-III. Yogi *et al.* (2026) assessed the impact of different Indian mustard varieties

and reported substantial yield improvements, ranging from 5 to 20%, highlighting the potential of varietal adoption in enhancing mustard productivity. Chand and Raju (2009) examined agricultural instability across technological and policy phases, highlighting yield stability as a crucial indicator for assessing crop performance and production reliability in India.

Growth performance: area expansion, production acceleration and productivity improvement

The growth analysis highlights that production expansion has been primarily driven by productivity improvement combined with selective area expansion. At the national level, Brassica area increased at an overall CAGR of 1.54%, while production registered a much higher growth rate of 3.79% and productivity increased at 2.22% annually

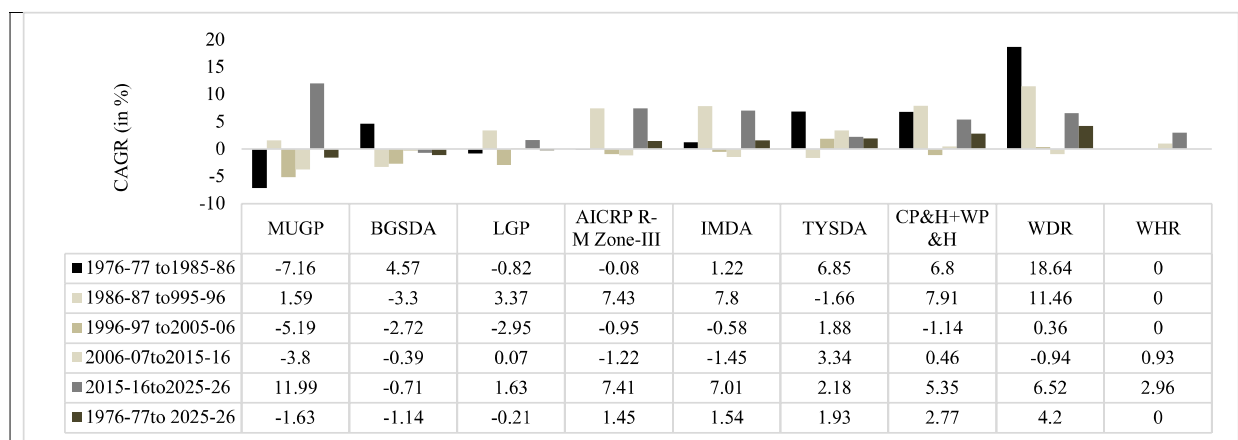


Fig. 2: Compound Annual Growth Rate (CAGR) in area of Oilseed Brassica across various agro-climatic zones over the five sub-periods in Zone-III (in %)

Source: Author's Estimates. *The IMDA/TYSDA/BGSDA aggregate includes other states outside Zone-III.

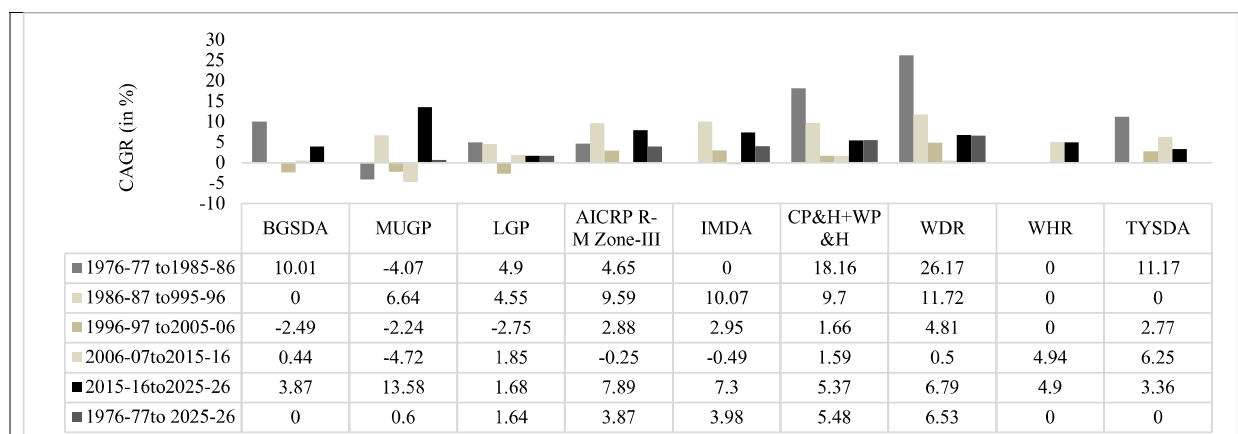


Fig. 3: Compound Annual Growth Rate (CAGR) in production of Oilseed Brassica across various agro-climatic zones over the five sub-periods in Zone-III (in %)

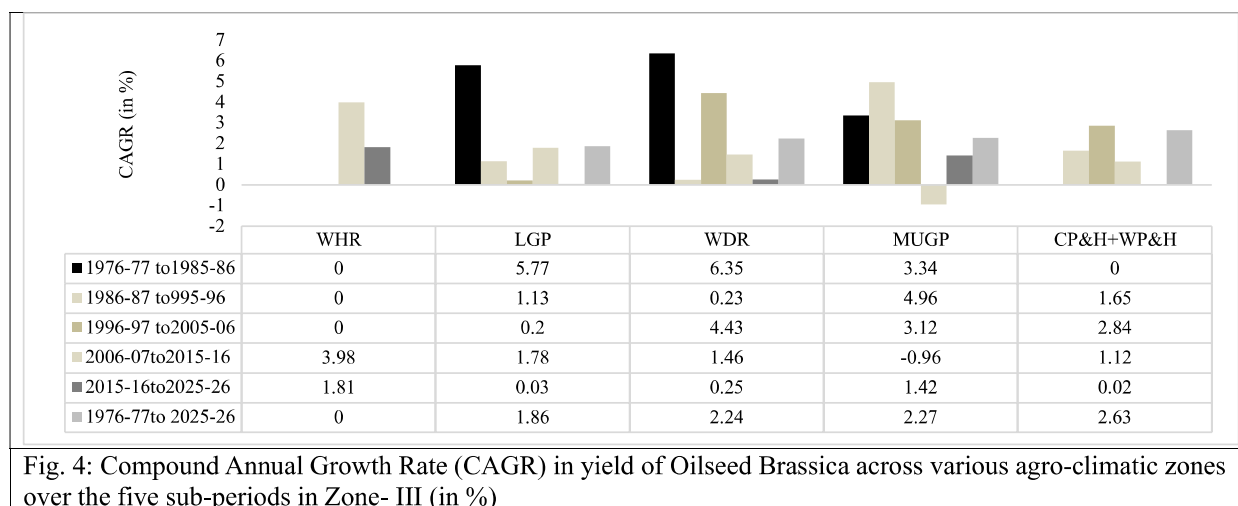
Source: Author's Estimates. *The IMDA/TYSDA/BGSDA aggregate includes other states outside Zone-III.

during 1976-77 to 2025-26. Similarly, the AICRP on Rapeseed-Mustard recommendation Zone III witnessed an overall CAGR of 1.45% in acreage and 3.87% in production. This confirms that technological advancement, improved genetic material and better production practices have played a dominant role in India's Brassica transformation. Chauhan *et al.*, (2016) reviewed India's seed sector, emphasizing quality assurance, seed-chain development, rising public-private participation, increased seed production, and policy support for improving seed and varietal replacement rates in field crops.

The TYSDA region recorded higher long-term area growth (1.93%) compared with IMDA (1.54%), demonstrating emerging opportunities for Eastern and North-Eastern India. Within the region, Western Dry Region recorded impressive area growth (4.20% annually) and production growth (6.53% annually), indicating successful adaptation of Brassica cultivation within existing cropping systems. Madhya Pradesh state from Central Plateau and Hills + parts of Western Plateau and Hills also showed rapid expansion during 2015-16 to 2025-26, with production growth exceeding 5% annually. Fig 2 reveals distinct temporal and regional shifts in Brassica area expansion. At the national level, area grew at 1.54% annually, driven primarily by rapid expansion during the Yellow Revolution and the hybrid phase. The Indian Mustard Dominated Area (IMDA) exhibited sustained long-term growth (1.54%), whereas the Toria and Yellow Sarson Dominated Area (TYSDA) recorded a relatively higher overall growth (1.93%), reflecting emerging opportunities in Eastern and North-Eastern India. Bihar experienced area contraction but substantial production growth due to strong productivity improvement. These

contrasting trends underscore the importance of region-specific market access, institutional support, and technology dissemination to sustain Brassica-based agricultural development. Productivity growth was the major contributor to sustainable production enhancement. National yield increased from 569 kg ha⁻¹ during the traditional period to 1,437 kg ha⁻¹ during the NMEO phase. Nevertheless, substantial yield gaps remain compared with leading mustard-producing states such as Rajasthan, Haryana and Madhya Pradesh. These differences indicate opportunities for targeted technology dissemination, improved seed replacement, precision production practices and stronger extension networks.

Fig 3 indicates robust long-term growth in Brassica production, with national output expanding at a CAGR of 3.79%, led by the Western Dry Region (6.53%) of the AICRP on Rapeseed-Mustard recommendation Zone III. The Toria and Yellow Sarson Dominated Area (TYSDA) also recorded sustained production growth, reflecting the increasing significance of Lower Gangetic Plain (Bihar). The accelerated growth in the AICRP on Rapeseed-Mustard recommendation Zone III highlights the region's untapped production potential. As per the CACP Report 2024-25, Rapeseed-mustard realized yield (13.9 q/ha) approached its potential (17.1 q/ha), with the lowest average yield gap (13.5%) among major rabi crops, indicating comparatively efficient productivity and substantial scope for bridging the remaining 18.7% potential yield gap. The potential increase in Rapeseed and Mustard production is estimated at 0.9 lakh tonnes can be obtained by reducing yield gap by 5%. Fig 8 depicts that productivity enhancement has been the principal driver of Brassica transformation. During 2015-16 to 2025-26, an improvement in yield was observed in all mustard



Source: Author's Estimates. *The IMDA/TYSDA/BGSDA aggregate includes other states outside Zone-III.

growing States of the AICRP on Rapeseed-Mustard recommendation Zone III ranging from 1.86% in Lower Gangetic Plain (Bihar) to 2.63% in Central Plateau and Hills + parts of Western Plateau and Hills (Madhya Pradesh), while Western Dry Region Rajasthan, which is dominating state, registered a little growth (0.25%) in the current period as compared to previous period (1.46%). As low or moderate growth was recorded in most of the major States, 2.22 % growth in yield was witnessed at all-India level during 1976-77 to 2025-26. In AICRP on Rapeseed-Mustard recommendation Zone III, positive long-term gains in Bihar indicate improving production efficiency, although considerable inter-state variability persists. The stagnant growth in yield (0.03%) across the lower Gangetic plains observed during 2015-16 to 2025-26 underscores the need for location-specific technologies, efficient market access, quality seed systems, and stronger local institutions to achieve

sustainable and inclusive Brassica development.

Stability analysis and sustainability concerns

Fig 5 highlights considerable instability in Brassica area dynamics across regions, as reflected by the Cuddy–Della Valle Index (CDVI). At the national level, area instability remained moderate (15.17), with the AICRP on Rapeseed-Mustard recommendation Zone III showing relatively higher fluctuations (22.75) due to the adjustments in the Middle and Upper Gangetic Plains (32.94). However, Lower Gangetic Plain and Western Himalayan Region demonstrated comparatively stable expansion. The Cuddy–Della Valle Index analysis indicates that production instability remains a major challenge. Nationally, instability was higher for production (19.54) compared with area (15.17), suggesting that climatic variability, yield fluctuations and market uncertainties significantly influence Brassica output (Fig

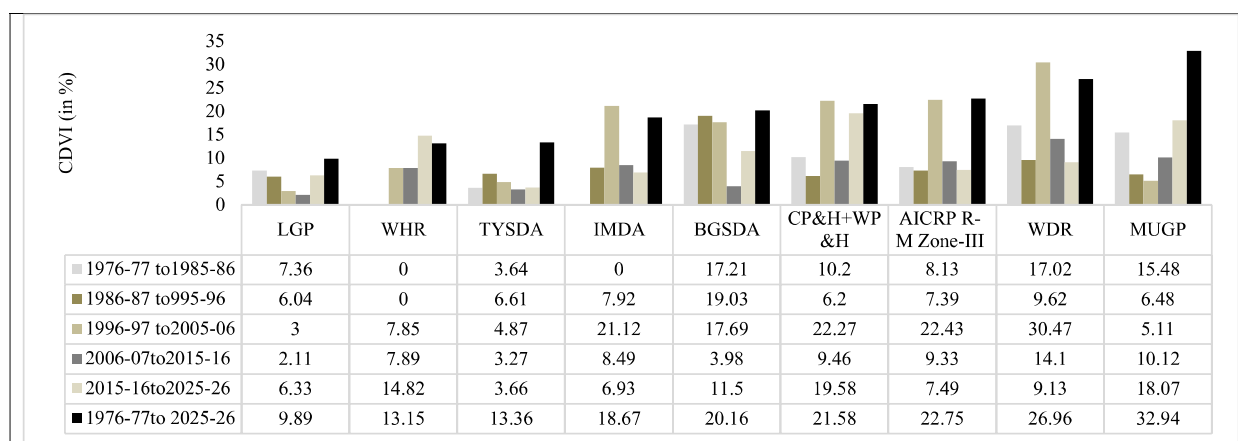


Fig. 5: Cuddy–Della Valle Index (CDVI) of area of Oilseed Brassica across various agro-climatic zones over the five sub-periods in Zone-III (in %)

Source: Author's Estimates. *The IMDA/TYSDA/BGSDA aggregate includes other states outside Zone-III.

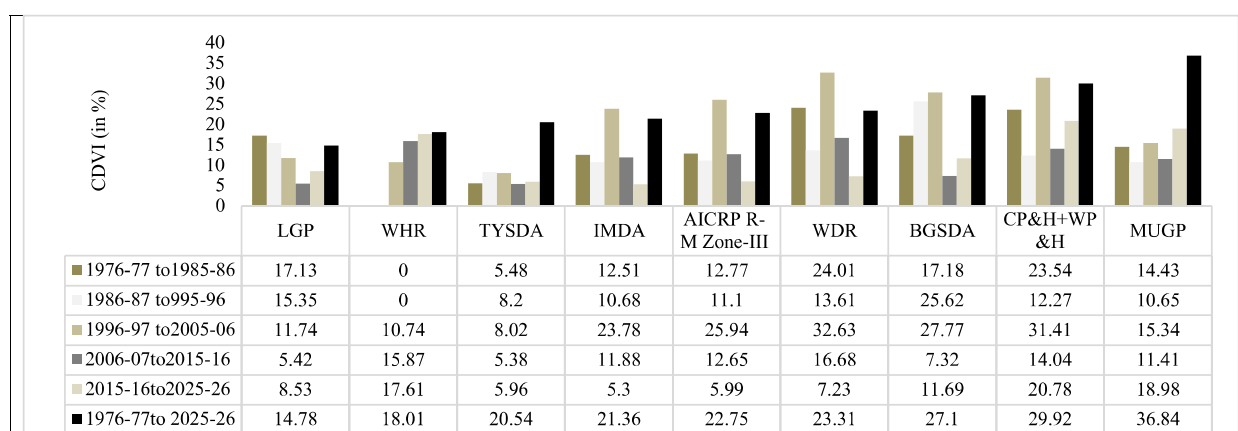


Fig. 6: Cuddy–Della Valle Index (CDVI) of production of Oilseed Brassica across various agro-climatic zones over the five sub-periods in Zone- III (in %)

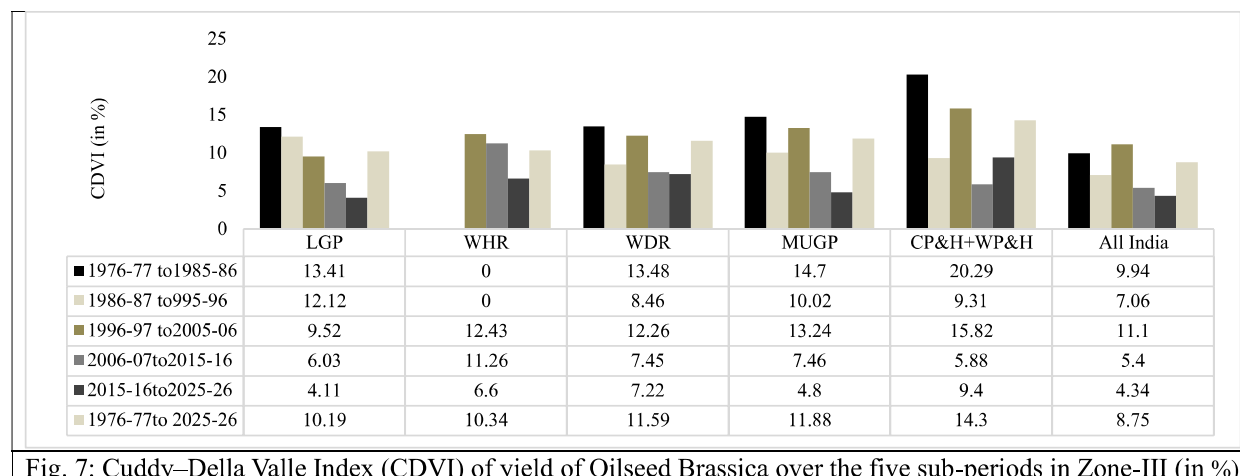


Fig. 7: Cuddy–Della Valle Index (CDVI) of yield of Oilseed Brassica over the five sub-periods in Zone-III (in %)

Source: Author's Estimates. *The IMDA/TYSDA/BGSDA aggregate includes other states outside Zone-III.

6). Yield instability remained comparatively lower, with the national CDVI of 8.75, indicating gradual technological stabilization. Lower Gangetic Plain (Bihar) and Western Himalayan Region exhibited improved yield stability during 2015-16 to 2025-26, suggesting benefits from technological interventions and improved management practices during recent periods. Similarly, Middle and Upper Gangetic Plains (Uttar Pradesh) also experience lower yield fluctuations during recent periods (Fig 7). Strengthening location-specific research, climate-resilient varieties, extension services, and farmer-oriented institutions is essential to minimize yield instability and promote sustainable Brassica intensification in the region.

Implications for sustainable Brassica development in Zone-III

The findings demonstrate that the AICRP on Rapeseed-Mustard recommendation Zone III showed significant Brassica-based agricultural transformation. The region's future growth is unlikely to emerge solely through area expansion; rather, it requires productivity enhancement and institutional strengthening. The increasing contribution of Central Plateau and Hills + parts of Western Plateau and Hills (Madhya Pradesh) and recently in Middle and Upper Gangetic Plains (UP) illustrates the feasibility of developing decentralized Brassica production clusters linked with local processing, seed systems and farmer organizations. The evidence suggests that sustainable Brassica development in the region requires a shift from production-oriented interventions towards integrated value-chain approaches. Improved market access, assured procurement mechanisms, farmer producer organizations, climate-resilient varieties, digital advisory services and region-specific extension strategies can reduce production risks and enhance farm profitability.

Policy implications

The transformation observed in leading Brassica-producing states demonstrates that productivity enhancement, assured markets and effective institutional support are critical drivers of long-term agricultural development. The findings of the study highlight that the AICRP on Rapeseed-Mustard recommendation Zone III possess considerable potential for productivity improvement across the Western Dry Region (Rajasthan), Central Plateau and Hills + parts of Western Plateau and Hills (Madhya Pradesh) and Middle and Upper Gangetic Plains (UP) with area expansion in the Lower Gangetic Plain (Bihar) and Western Himalayan Region (Uttarakhand). However, realizing this potential requires region-specific policy interventions addressing technological, institutional, infrastructural and market-related constraints. The period of TMO witnessed CAGR 3.37, 6.97 and 3.47% in oilseeds, and 5.82, 8.72 and 2.73% in oilseed brassica in terms of area, production and yield, respectively. The growth was achieved mainly due to development of new varieties, technological advancements in production and protection, and policy interventions during this period. During post-TMO, there was a setback in the area, production and productivity which is a serious concern and underlines needs to revisit the policy outlines to increase the production of oilseeds as well as oil to attain self-sufficiency in edible oils (Jat *et al.*, 2019).

Strengthening region-specific production strategies

The diversity of Brassica production systems across various climatic zones requires differentiated policy approaches rather than uniform interventions. While Rajasthan, Uttar Pradesh and Madhya Pradesh have benefited from improved varieties, mechanization and developed market systems, states such as Bihar and

Uttarakhand require strategies tailored to smallholder-based production systems. About 98% of the cultivated Indian soils required phosphorus fertilization for getting better yield (Bhari *et al.*, 2000 and Singh *et al.*, 2010). Nutrient uptake data in rapeseed-mustard show that it removes as much K as N (NAAS, 2009). Total Factor Productivity (TFP) growth is inadequate to move towards oilseeds / edible oil self-sufficiency and demands a shift in production technology (Balaji *et al.*, 2021). Expansion of Brassica cultivation in Lower Gangetic Plain should be promoted through location-specific varieties, short-duration cultivars and climate-resilient technologies. Productivity augmentation may be instrumental in self-sufficiency of edible oils (Gulati 1996).

Improving quality seed systems and technology dissemination

The potential productivity gaps across the mustard-growing regions indicate the need for strengthening seed replacement systems, decentralized seed production and timely availability of quality planting material. Kumar *et al.* (2006) highlighted that Technological change through the development of varieties for different conditions has helped to improve yield ranging 9 to 45 % in irrigated conditions. Chauhan *et al.* (2016) highlighted that a robust, quality-assured seed system, supported by public-private partnerships and policy reforms, is fundamental for sustaining agricultural productivity, varietal replacement, and food security in India. Public-private partnerships involving ICAR institutes, state agricultural universities, Krishi Vigyan Kendras and farmer organizations can accelerate dissemination of improved Brassica varieties and production technologies. Strengthening extension networks and digital advisory platforms will help farmers adopt scientific crop management practices. The potential of canola quality varieties in India is clearly depicted in the experience of Punjab Agro Food Grains Corporation, which took up the cultivation of Hybrid *Brassica napus* (Hyola) in Punjab (Kumar *et al.*, 2009).

Enhancing market access and value-chain integration

Trends highlight the need for establishing regional Brassica grain aggregation centres, modern oil extraction units and Farmer Producer Organizations (FPOs) to improve market integration and increase value realization. Linking producers with service providers (Seed and Sulphur containing fertilizers), institutional buyers and edible oil industries can create stable demand and reduce market uncertainty. The growth in oilseed production during the pre-green revolution period was mainly

through area expansion in most of the crops. Along with the minimum support price program, projects to evolve and transfer new technologies to farmers' fields were initiated during 1980's. The price parity between oilseed crops and cereals were adjusted many times in favour of oilseed crops during 1980s. Between 1978-79 and 1985-86, while the price support for paddy was increased by 67%, it was increased by 100% for groundnut. Similarly, the price support for wheat in this period was increased by 41%, whereas it was 63% for rapeseed-mustard (Acharya 1993). Eco-regional variations are mainly noted due to biophysical fittingness of the crop. The long-term trends in area are declining in most of the States, however, production and yields have increased. The concept of eco-regional approach can effectively be utilized to realize potential yields with high input use efficiency in these regions. Supporting services like input supply, marketing and processing have to be linked to these ecological zones besides strengthening research and extension systems, and infrastructure facilities.

Building climate-resilient and sustainable production systems

The high production instability highlights vulnerability of Brassica crops to climatic variability and production risks. Policies should promote climate-smart Brassica cultivation through stress-tolerant varieties, improved water management, conservation agriculture practices and weather-based advisory services. According to Agro-Economic Research (2013) rapeseed-mustard recorded high compound annual growth rates in area, production, and productivity during the 1980s and 2000s in Rajasthan. However, these gains were accompanied by considerable year-to-year variability, reflecting production instability. In contrast, such pronounced fluctuations were not observed in the competing wheat crop, indicating relatively greater stability in its growth trajectory.

Strengthening local institutions and inclusive development

Local institutions play a crucial role in converting technological gains into sustainable livelihoods. Strengthening farmer cooperatives, seed hubs, self-help groups and FPOs can improve access to inputs, credit, extension and markets. Overall, policy support should move beyond production enhancement towards a holistic ecosystem approach integrating technology, markets, institutions and sustainability. Intensive agriculture demands more as the farm energy consumption increases. Farm power availability increased from 0.293 kW/ha in 1971-72 to 2.543 kW/ha in 2019-20 (Singh S., 2026). Such an integrated framework can transform Zone III into a

resilient hub of Brassica cultivation, contributing significantly to India's edible oil self-reliance and sustainable agricultural development goals. Yogi *et al.* (2024) examined rapeseed-mustard productivity trends across agro-climatic zones of Jharkhand during 2000-01 to 2019-20. The study reported substantial spatial and temporal variability in productivity and identified significant productivity gaps, emphasizing targeted technological interventions, improved policy implementation, and strategic planning to enhance rapeseed-mustard productivity in disadvantaged areas.

Conclusion

The study demonstrates that Brassica cultivation in India has undergone significant structural transformation during 1976-77 to 2025-26, with production growth increasingly driven by technological advancement, productivity enhancement and improved production systems. While the AICRP on Rapeseed-Mustard recommendation Zone-III continues to dominate national production, other zones, has also emerged as an important region with considerable potential for future expansion. The analysis reveals that various agro-climatic zones have experienced encouraging growth in area, production and productivity, reflecting opportunities for Brassica intensification in diverse agro-ecological environments. However, high production instability in several regions highlights persistent challenges related to climatic variability, fragmented markets, inadequate infrastructure, weak seed systems and limited institutional support. The future pathway for sustainable Brassica development in Zone-III lies in integrating technological innovations with efficient markets, strong local institutions and resilient value chains. Region-specific varieties, improved extension services, farmer producer organizations, processing infrastructure and assured market linkages can enhance productivity, profitability and sustainability. The declining yield performance over recent five-year periods further underscores the need to examine the underlying causes of productivity stagnation or decline rather than focusing exclusively on area expansion. For further research, area substitution among competitive crops such as wheat, gram and barley should be examined to explain Brassica expansion or contraction. Additionally, cost of cultivation and production, SRR, VRR, Hybrid promotion and quality preferences, MSP, Rabi Season Market (RMS) prices, market demand and related factors, biotic and abiotic stresses, warrant systematic investigation. Thus, transforming Brassica cultivation in the region requires a shift from production-centric approaches towards an integrated ecosystem model that combines productivity enhancement, market access and

institutional strengthening. Such strategies will not only improve farmers' livelihoods but also contribute significantly to India's goal of edible oil self-reliance and sustainable agricultural development.

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