



SEEDS OF SELF-RELIANCE: ROLE OF PLANT BREEDING IN INDIA'S OILSEED MISSION

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INTRODUCTION

India's quest for self-reliance in edible oils is among the most consequential agricultural challenges of the present decade. With a population of 1.4 billion and per capita consumption rising with incomes and urbanisation, India's edible oil demand stands at approximately 25 million tonnes annually. The paradox is structural rather than cyclical: India is home to 18% of the world's population, yet domestic production meets only about 44% of its edible oil requirement, and imports account for the remaining share at a cost of roughly \$21 billion in foreign exchange each year. This import dependence is well documented in the sector literature, which shows consumption consistently outpacing production and a consequent reliance on imports for roughly 60% of annual consumption (Singh, 2021), with short supply driven by population growth, rising incomes and dietary change (Chandrashekhar, 2023). Dependence of this order is a strategic exposure, not merely an economic one: global supply chains, volatile international prices and geopolitical disruption translate directly into domestic availability and affordability. The COVID-19 pandemic and recent international conflicts demonstrated how rapidly import dependence can become a crisis, with consequences for household budgets and for industries that use vegetable oils as raw material. Achieving greater self-reliance is consequently central not only to agricultural growth, but also to food security, macroeconomic stability and national resilience.

History: From Yellow Revolution to Import Dependence

India's progress toward oilseed self-sufficiency is best read through its agricultural policy history. The Technology Mission on Oilseeds (TMO) was launched in 1986 (Renjini & Jha, 2019), and the years that followed the late 1980s and early 1990s are the period properly described as the “Yellow Revolution.”

Irrigated area under rapeseed-mustard, for instance, rose steadily from 51.3% in 1985-86, the year the TMO was launched (Kumar & Chauhan, 2005). During this period, oilseeds recorded compound annual growth rates of 3.37% in area, 6.97% in production and 3.47% in yield, while oilseed brassica achieved 5.82%, 8.72% and 2.73% respectively (Jat *et al.*, 2019). Domestic production met the bulk of consumption and imports remained marginal. The achievement rested on coordinated government support minimum support prices, import substitution and sustained research investment and it established the institutional architecture that later policy would build upon.

Economic liberalisation in the early 1990s altered this trajectory. India's decision in 1994-95 to permit free trade in edible oils under Open General License, together with a reduction in the edible-oil import duty from 65% to 15%, exposed the domestic sector to heavy imports and depressed domestic prices (Renjini & Jha, 2019). Subsequent trade agreements and periodic duty revisions further reshaped the sector's competitive position. The result was a steady erosion of self-sufficiency, and a policy environment in which domestic oilseed prices were increasingly set by international markets rather than by domestic supply conditions. The period that followed shows how trade exposure translated into structural dependence. Imports grew at 9.36% annually, substantially outpacing domestic production growth, and palm oil from Indonesia and Malaysia came to dominate the import basket, followed by soybean and sunflower oils from South America and Eastern Europe, with palm oil accounting for roughly 59–63% of imports, soybean for about 23% and sunflower for about 16% (Ponnaganti *et al.*, 2025). Import volume reached 14.28 million tonnes in 2021-22 (Rao, 2023) and 15.66 million tonnes in 2023-24. This composition of imports dominated by a single oil from a narrow set of origins is itself a risk concentration, and it exposes both consumers and foreign exchange reserves to price shocks originating outside India's control.

The Policy Response and NMEO Framework

Recognising the strategic cost of import dependence, the Government of India launched the National Mission on Edible Oils–Oil Palm in August 2021 with an outlay of ₹11,040 crore, followed by the National Mission on Edible Oils–Oilseeds (NMEO- Oilseeds), approved by the Union Cabinet in 2024 for 2024-25 to 2030-31 with an outlay of ₹10,103 crore. Together they form a two-pronged response, and in the policy literature both are described as successors to the oilseed component of the National Food Security Mission (Barik, 2023). The missions combine area expansion, productivity improvement through better seed, processing infrastructure and market linkage.

NMEO-Oilseeds targets primary oilseed production of 69.7 million tonnes by 2030-31, up from 39 million tonnes in 2022-23, which requires productivity to rise from 1,353 kg/ha to 2,112 kg/ha. On the oil palm side, the mission targets output rising to 11.20 lakh tonnes by 2025-26 and 28 lakh tonnes by 2029-30, with an additional 6.5 lakh hectares brought under cultivation from a base of about 4.5 lakh hectares (Gandhe *et al.*, 2023). The scale of the productivity targets a roughly 56% increase in per-hectare output is the element that makes plant breeding the binding constraint on the mission's success rather than a supporting instrument.

Traditional Breeding and Its Limitations

Conventional plant breeding has been the backbone of oilseed improvement in India. It involves identifying plants with desirable traits and crossing selected parents to combine favourable characteristics, followed by successive generations of selection and multi-location evaluation. However, the limitations of this approach are well recognized. Phenotypic selection is influenced by environmental variation and genotype $\times$ environment interactions, which can reduce selection accuracy, particularly for traits with low to moderate heritability. In addition, the conventional breeding cycle is relatively long

because several generations of segregation, selection, advancement and multi-environment testing are generally required before a superior genotype can be released as a variety. The expected rate of genetic gain can be conceptualized by the breeder's equation, $\Delta G = \sigma A \times i \times r/L$, where σA is the additive genetic standard deviation, i is selection intensity, r is selection accuracy, and L is the length of the breeding cycle. Molecular and genomic approaches can contribute particularly by increasing selection accuracy, enabling earlier selection and shortening the breeding cycle, while also facilitating the efficient utilization of genetic variation (Crossa *et al.*, 2017).

The complexity is further amplified in polyploid oilseed crops. Indian mustard (*Brassica juncea*) is an allotetraploid with an AABB genome and $2n = 36$ chromosomes (Rana *et al.*, 2019), and its polyploid genome can complicate allele tracking, recombination and the introgression and fixation of specific traits (Ahmad *et al.*, 2023). Cultivated groundnut (*Arachis hypogaea* L.) is also an allotetraploid (AABB; $2n = 4x = 40$) and is more appropriately described as a segmental allotetraploid because it exhibits predominantly disomic but also appreciable homeologous/tetrasomic recombination. These genomic features can make precise trait introgression and selection more challenging. Reproductive biology also influences breeding strategy. Indian mustard is predominantly self-pollinated but exhibits variable levels of outcrossing. At the same time, its strong heterotic potential and the availability of cytoplasmic male-sterility systems provide opportunities for F1 hybrid breeding (Kumar *et al.*, 2023). Finally, oilseed improvement is inherently a multi-trait problem: breeders must simultaneously improve seed yield, oil content, fatty-acid composition, disease resistance and tolerance to abiotic stresses. Correlations and trade-offs among these traits can further complicate phenotypic selection and necessitate more precise approaches such as marker-assisted selection, genomic selection, high-throughput phenotyping and molecular breeding.

Modern Breeding Technologies: A New Paradigm

Marker-Assisted Selection

MAS shifts selection from phenotype to genotype: DNA markers linked to target traits allow plants to be selected on genetic constitution rather than appearance, which is particularly valuable for traits that are difficult to score or are expressed only under specific conditions. Its underlying rationale is that pyramiding major and minor genes confers more durable resistance than reliance on single genes (Singh *et al.*, 2021), and marker-assisted selection combined with phenotypic selection provides a workable route to validated disease-resistance loci in *B. juncea* (Inturrisi *et al.*, 2020). In Indian mustard, this approach has been applied to combine white rust resistance, low erucic acid content and reduced glucosinolates, with pyramided lines reported at over 90% recurrent parent genome recovery in cultivars DRMR150-35 and NRCHB101.

Genomic Selection

GS estimates genome-wide marker effects and uses them to predict breeding values, allowing selection of superior genotypes at higher accuracy and earlier in the cycle (Crossa *et al.*, 2017). Because it captures the small effects of many loci, it is better suited than MAS to complex, quantitatively inherited traits, and for quantitative disease resistance it has been shown to outperform MAS marker-regression approaches (Poland & Rutkoski, 2016). In soybean the approach can shorten breeding cycles substantially and enables selection for traits that are costly or slow to phenotype (Sun *et al.*, 2026).

Genome Editing

Site-directed nuclease systems such as CRISPR-Cas9 allow targeted modification of specific genes. Precise, transgene-free edits are now demonstrated in oilseed brassicas: CRISPR-Cas12a knockout of the multicopy myrosinase gene family in allotetraploid *B. juncea* reduced pungency in fresh leaves stably across environments (Karlson *et al.*, 2022), and

knockout of *BnFAEI* raised oleic acid to 70–80% while reducing erucic acid (Ambrin & Eram, 2024). Such edits fall within the regulatory category of site-directed nuclease products rather than transgenic events, which is a materially different regulatory pathway though editing multiple homoeologous copies in polyploids remains a technical constraint.

High-Throughput Sequencing and Genotyping

Falling sequencing costs have produced high-density genetic maps and reference genomes for the major oilseed crops, enabling more targeted identification of trait-associated loci. These genomic resources underpin both marker development and the training populations required for genomic prediction (Thudi et al., 2020), and their convergence with high-throughput phenotyping is the central enabling development in contemporary crop breeding (Cabrera-Bosquet et al., 2012).

Specific Breeding Achievements by Crop

Rapeseed-Mustard

Mustard breeding in India has been systematic and cumulative. Under the All India Coordinated Research Project on Rapeseed-Mustard, 248 varieties have been released, of which 185 are notified, spanning Indian mustard, toria, yellow sarson, gobhi sarson, brown sarson, karan rai, taramira and black mustard, together with six hybrids. The hybrid programme has a documented lineage: PGSH 51 (1994, tour CMS) was the first commercial brassica hybrid, followed by Hyola 401 (2000), NRCHB-506 (2008, mori cytoplasm), DMH-1 (2008) and PAC-432 (2009) (Chand et al., 2021). NRCHB-506 is credibly described as transformative for mustard production in northern India (Chand et al., 2021), and its hybrid seed-production technology has since been formally standardised (Maity et al., 2012). Recent varieties such as DRMRCI (Q) 172 yield 2,304 kg/ha with 41.8% oil content, combining white rust and *Alternaria* blight resistance with low erucic acid. Mustard

production rose from 4.2 million tonnes in 2010-11 to 8.5 million tonnes in 2023-24.

Soybean

The development of Kunitz trypsin inhibitor-free soybean is one of the clearest applications of marker-assisted backcrossing in Indian oilseed breeding. The null KTI allele was sourced from the donor line PI542044 and introgressed into the recurrent parents DS9712 and DS9814 (Shivakumar et al., 2016) and into JS97-52 (Kumar et al., 2015), with recovery of 96–98% of the recurrent parent genome (Talukdar et al., 2014) and trypsin inhibitor content reduced by 68.8–83.5%, against 83.37 and 123.96 mg/g seed meal in the recurrent parents. The released material yields 1,229 kg/ha, with 33.14% protein and 20.19% oil content and 113-day maturity, and carries resistance to Yellow Mosaic Virus and Soybean Mosaic Virus.

Groundnut

Groundnut breeding has advanced both productivity and quality. High-oleic lines developed through marker-assisted backcrossing and marker-assisted selection using *FAD2A/FAD2B* allele-specific markers raised oleic acid from about 60% in the parents to about 80% (Pandey et al., 2020); high-oleic peanuts are defined by an oleic acid content of at least 78% (Kamdar et al., 2022) and typically reach $80 \pm 2\%$, against 45–50% in normal peanuts (Janila et al., 2018). The Indian cultivars ICGV 181030, developed with the University of Agricultural Sciences Dharwad, contains 78–81% oleic acid and recorded a 7% yield increase over three years of testing in Zone IV, while ICGV 201214, developed with Junagadh Agricultural University, recorded a 19% improvement in kernel yield over JL 501 in Zone II. For comparison, the widely grown variety K 6 contains about 48% oil, approximately 40% oleic acid and about 38% linoleic acid. These varieties command a price premium, since high oleic acid content extends shelf life and meets the requirements of food processors.

Sunflower and Other Oilseeds.

Sunflower cultivation in India is constrained by its high-water requirement, drought and heat sensitivity, and competition from crops such as soybean, maize and cotton. Its production has declined from earlier peak levels, when national output approached approximately 0.6–0.7 million tonnes, to roughly 0.1–0.2 million tonnes in recent years. Average productivity is generally around 700–1,000 kg/ha, although well-managed irrigated fields can exceed 1,500 kg/ha. These figures indicate a substantial yield gap between farmers' fields and the crop's attainable yield potential.

Breeding has consequently concentrated on developing short-duration, high-yielding and disease-resistant varieties suited to different agro-climatic zones. Short-duration types, usually maturing in about 90–120 days, can be incorporated into rice-fallow and multiple-cropping systems. With an average seed-oil content of approximately 35–45%, the production of 0.1–0.2 million tonnes of sunflower seed could provide roughly 35,000–90,000 tonnes of oil before processing losses. Therefore, even a 20–30% improvement in productivity could generate an additional approximately 20,000–60,000 tonnes of seed, depending on the cultivated area and baseline yield. Although sunflower represents a smaller share of India's total edible-oil supply than soybean, rapeseed–mustard and groundnut, its contribution to the oil mission lies in diversification, regional adaptation and efficient use of fallow land. Breeding varieties with improved oil content, drought and heat tolerance, resistance to downy mildew and *Alternaria* leaf blight, and greater yield stability can increase domestic oil production without proportionately expanding cultivated area. Similar breeding gains in rapeseed–mustard, soybean, groundnut, sesame, safflower and linseed are essential for raising national oilseed productivity and reducing dependence on imported edible oils. Exact production, productivity and contribution figures should be reported for a specified agricultural year using a consistent official dataset.

Impact Assessment: Measuring the Transformation

Primary oilseed production reached 42.609 million tonnes in 2023-24, against the 69.7 million tonne target for 2030-31 — a gap that underscores how much depends on accelerated adoption of improved varieties and management. Yield gains have been most visible where improved varieties have been widely adopted. In the mustard-growing regions of northern India, average yields rose from 900–1,000 kg/ha in the early 2000s to 1,200–1,500 kg/ha in recent years, and in groundnut cultivation in Gujarat and Maharashtra yields rose from 800–1,000 kg/ha to 1,500–2,000 kg/ha with the adoption of improved varieties and better management.

The economic returns to improved varieties extend beyond yield. High-oleic groundnut commands a price premium over regular varieties because of its oil quality and demand from processors and health-conscious consumers, and this premium accrues directly to farm income. Disease resistance is a second and larger source of economic value: white rust-resistant mustard varieties protect farmers in the northern mustard belt from severe losses, and disease-resistant soybean varieties reduce losses from viral diseases. At the processing level, oilseed cultivation exerts a multiplier effect through oil extraction units and refineries, which provide employment and value addition, while the seed production sector has grown with private investment in production infrastructure and quality assurance.

Improved varieties contribute to nutritional security through two channels: increased domestic production improves the availability and affordability of edible oils as sources of calories and essential fatty acids, and quality improvement through breeding raises their nutritional value. High-oleic varieties offer a more favourable fatty acid profile, with a higher share of monounsaturated fat, and thus a potential contribution to cardiovascular health. Breeding also contributes to environmental sustainability through several pathways. Higher yield per hectare reduces the

pressure to bring additional land under cultivation, helping preserve natural ecosystems; disease-resistant varieties reduce the need for chemical pesticides; and improved water-use efficiency supports sustainable water management in water-scarce regions.

Challenges and Strategic Considerations

Climate change is the central threat to oilseed production, through more frequent extreme weather, rising temperatures and erratic rainfall. Breeding must therefore target drought tolerance, heat resistance and flood tolerance, with particular attention to heat stress during flowering and seed development — critical stages at which high temperatures reduce yield substantially. Genomic tools are directly relevant here: marker-assisted selection, genomic selection and gene editing are the recommended toolkit for climate-resilient oilseed crops (Iqbal et al., 2026), and combining genomic information with high-throughput phenotyping and remote sensing accelerates the identification of tolerance traits (Benitez-Alfonso et al., 2023). Drought-tolerant material with deeper root systems and improved water-use efficiency is specifically needed for the rainfed areas where much oilseed cultivation is concentrated.

Adoption by smallholder farmers is the second constraint. The value of an improved variety is realised only through effective seed distribution, farmer training and demonstration plots, and digital advisory tools — mobile applications, advisory services and drone-based monitoring can help close the extension gap. Market integration is the third: realising the full economic benefit of improved varieties requires storage and processing capacity, market information systems and farmer-producer organisations capable of aggregating produce and negotiating prices, with contract farming offering assured markets and quality grading providing access to premium segments. Finally, sustained progress depends on research infrastructure and human resources — strengthened ICAR institutions, agricultural

universities and private programmes, and a next generation of breeders trained in modern breeding technologies, with public-private partnerships aligning breeding objectives with farmer needs and market demand.

Future Directions

The next phase of oilseed breeding will depend on integrating genomics, phenomics and data analytics. Genomic selection is expected to become routine for complex traits such as yield, supported by breeding platforms that combine marker information with environmental data. High-throughput phenotyping using drones, sensors and imaging will allow rapid evaluation of large populations across diverse environments. Gene editing will be applied to targets that are difficult to address by recombination improved fatty acid profiles, reduced anti-nutritional factors, and stress tolerance within a regulatory framework that is still evolving in India and elsewhere. Breeding for climate adaptation will focus on heat tolerance at critical growth stages, drought resistance through root architecture and water-use efficiency, and yield stability under variable conditions. Nutritional enhancement will extend to improved fatty acid profiles, micronutrient content and protein quality. Digital platforms, machine learning and remote sensing will accelerate phenotypic data collection and prediction accuracy, with traceability systems supporting quality assurance through the seed supply chain.

CONCLUSION

India's progress toward oilseed self-reliance depends on translating scientific capacity into farmer-level productivity. The missions constitute the institutional framework; plant breeding is the instrument that determines whether the productivity target is attainable. The evidence reviewed here shows measurable gains: high-yielding mustard varieties with superior oil quality, KTI-free soybean lines developed by marker-assisted backcrossing with 96–98% recurrent parent genome

recovery, and high-oleic groundnut cultivars containing 78–81% oleic acid. These are productivity, quality and risk-reduction outcomes simultaneously, and they are the mechanisms through which the import bill is reduced.

Realising this potential, however, depends on factors outside the breeding programme. Adoption by smallholders requires functioning extension and seed systems; price realisation requires value chains that reward quality; and continued progress requires investment in research infrastructure and in breeders trained in modern methods. Two limitations of this review should be stated: the quantitative evidence draws substantially on official statistics with differing base years and on institutional reports, and varietal performance data are drawn largely from coordinated trial results rather than from independent multi-year farm-level assessment. Addressing both would strengthen the evidence base for future policy.

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