GreenariA
Go Green, Learn Green

Special Issue

VOLUME 4 e-ISSN: 2584–153X SPL ISSUE 1

Five Days

INTERNATIONAL WORKSHOP & FARMERS' FAIR

Bridging Research and Field Practices for Agrœcological Farming Systems and Oilseed-Based Sustainable Development in Tribal Hilly Regions

(Under Scheduled Tribe Component)[TSP]

Organized by

Department of Agriculture

Central University of Odisha, Koraput, India

In collaboration with

ICAR-Indian Institute of Rapeseed-Mustard Research, Bharatpur, Rajasthan, India

2026

Published By:

GreenariA



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Go Green, Learn Green

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Chidambaram - 608002, Tamil Nadu, India
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e-ISSN: 2584–153X Volume 4 , Spl. Issue 1, 2026

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EDITORIAL

Agriculture in tribal and hilly regions represents far more than a means of food production; it embodies a way of life, a repository of indigenous knowledge, and a foundation for sustainable livelihoods. The Koraput region of Odisha, characterized by rich agro-biodiversity, diverse farming traditions, and predominantly tribal communities, possesses immense potential for developing resilient and sustainable agricultural systems. However, challenges such as climate variability, low productivity, fragmented landholdings, soil degradation, and limited market access continue to constrain agricultural growth and livelihood security in the region.

Recognizing the need for context-specific and sustainable agricultural solutions, this special issue of GreenariA is published in conjunction with the International Workshop and Farmers' Fair on "Bridging Research and Field Practices for Agroecological Farming Systems and Oilseed-Based Sustainable Development in Tribal Hilly Regions." The issue provides a platform for sharing scientific innovations, field experiences, indigenous knowledge, and sustainable practices that strengthen agroecological farming systems and improve the livelihoods of tribal communities.

The articles cover diverse themes, including climate-resilient oilseed production, agroecological farming, natural resource management, sustainable plant health, digital agriculture, mechanization, value addition, agribusiness, and policy innovations. Special emphasis is given to oilseed-based farming systems for enhancing crop diversification, nutritional security, income generation, and climate resilience in tribal hilly regions. This issue highlights the importance of integrating research, extension, policy, and indigenous knowledge to promote resilient, resource-efficient, and sustainable agricultural systems, contributing to long-term livelihood security and inclusive rural development.

We hope that this issue will serve as a valuable resource for researchers, students, policymakers, extension professionals, development practitioners, and farmers. It is our sincere belief that the knowledge and experiences shared herein will contribute to advancing agroecological farming systems, sustainable oilseed development, and climate-resilient livelihoods, thereby supporting a more prosperous and sustainable future for tribal hilly communities.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine

Volume 04, Special Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-01

MARKER-ASSISTED BREEDING FOR CLIMATE-RESILENT OILSEED VARIETIES IN TRIBAL HILLY ECOSYSTEMS

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Introduction

Ecological sensitive agriculture for food security in tribal hilly region of India and South Asia. The areas are typified by hilly terrain, erratic rainfall, low soil fertility and limited access to modern inputs. However, indigenous communities have managed to farm in these regions for centuries using traditional cultivars and a variety of landraces. "But with climate change and population growth, we need better crop varieties that can cope with the specific biotic and abiotic stresses of these environments.

Conventional breeding under these conditions is slow, labour intensive and prone to genotype x environment (G x E) interactions as it is dependent on phenotypic selection through several seasons. Phenotypic selection is particularly unreliable as important climate resilience traits such as drought tolerance, disease resistance and oil-quality parameters are controlled by quantitative trait loci with small individual effects.

Marker assisted breeding overcomes these limitations by allowing the selection of DNA markers linked to the target gene or QTLs irrespective of growth stage, dominance effects or environmental conditions. It is an efficient, accurate and reliable approach for breeding climate resilient oilseed varieties suited to the agro-climatic and socio-economic conditions of tribal hilly farming system (Chugh *et al.,* 2022*)*.

What is Marker Assisted Breeding?

MAB is a modern plant breeding technique, which uses molecular markers (i.e. identifiable DNA segments at known locations on chromosomes) as indirect tools for selection of agriculturally important traits in crop improvement programmes. Though environmental factors can influence the phenotypic expression of a trait, MAB directly studies the genotype at the DNA level and enables the selection of individuals with target genes or gene combinations with high accuracy and efficiency.

Basic Steps Involved in Marker-Assisted Breeding

Marker Identification Target Genes Associated with: The process begins with QTL mapping or association studies where molecular markers across the genome are genotyped in segregating populations (F2, BC1 or RILs). Using statistical analysis, markers that are tightly linked to the trait of interest are identified and validated before being used in breeding programs, ideally within 5cm*)*.

Crossing of Parents: An elite recipient parent is crossed with a donor parent carrying the desired gene (e.g. disease resistance) to get F1 hybrid. This hybrid is selfed or backcrossed to the recurrent parent. The main objective is to introduce the target gene in the elite background with the minimum amount of undesirable donor chromatin, a phenomenon called linkage drags.

Marker Screening of Progenies: Genotyping of F1/F2/BC progenies using molecular markers on gel electrophoresis/capillary electrophoresis/SNP platforms from DNA isolated from young leaf. Plants are scored as AA, Aa or aa at marker loci. This screening can be carried out at the seedling stage, greatly accelerating the selection process.

Selection desirable: Plants with target allele at flanking markers in an elite background selected for advancement. Gene pyramiding is only effective when the plants contain all the target alleles. Background selection with genome-wide markers can recover >98% of the recurrent parent genome in only two backcross generations as compared with 5-6 generations in conventional breeding.

Development of variety: Plants are selfed to make them homozygous and then tested in replicated multi-environment trials in different agro-climatic zones including tribal hilly areas. Lines meeting Distinctness, Uniformity, Stability and Value for Cultivation and Use criteria are recommended for official release as new varieties.

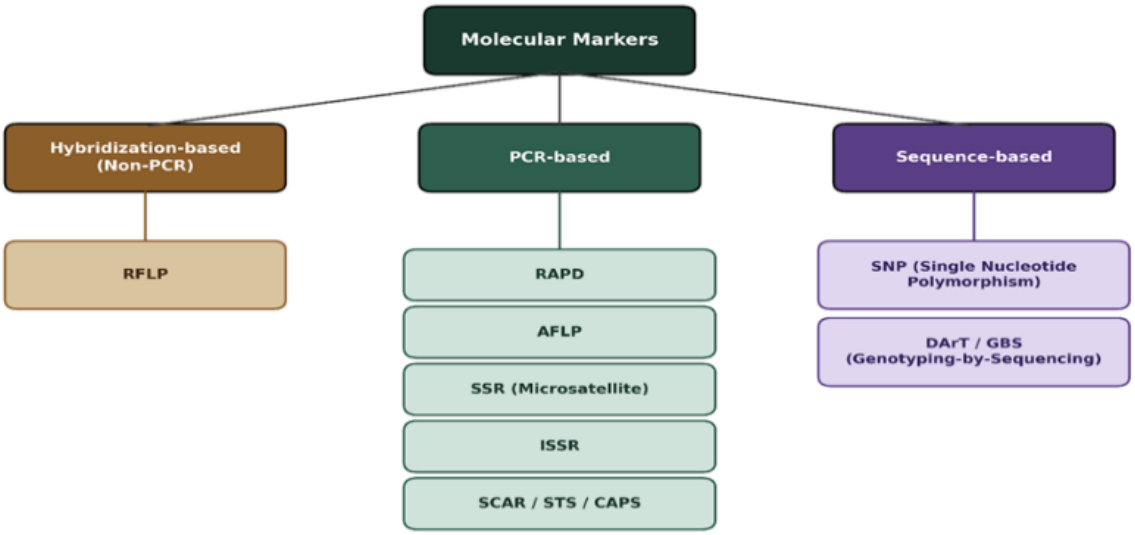


Figure 1. Classification of molecular markers used in marker-assisted breeding of oilseed crops, grouped by detection technique

Types of molecular marker used in it

SNPs are the most widely used markers in modern MAB programs due to their (i) very high density in the genome (millions per genome), (ii) bi-allelic and co-dominant nature permitting discrimination of all three genotypic classes, (iii) suitability for high-throughput genotyping platforms such as SNP arrays, Genotyping-by-Sequencing and KASP assays and (iv) compatibility with next generation sequencing technologies (Varshney *et al.,* 2014). SSR (microsatellite) markers are still popular for MAB in developing countries especially in tribal zone breeding programs due to their cost effectiveness, co-dominance, high polymorphism and availability of established marker panels for the major food crops such as rice, wheat and maize.

Marker assisted breeding in oilseed crops – applications

Resistance to Disease and Pests: The losses in groundnut yield due to foliar diseases like rust (*Puccinia arachidis*) and late leaf spot are to the tune of 57%, especially in rainfed and tribal farming areas . SSR markers linked to resistance QTLs on linkage groups AhXII and AhXV such as GM1009, GM1536, GM2079, GM2301 and

IPAHM103 have been utilized in marker-assisted backcrossing for introgression of durable resistance in popular varieties such as JL 24 and TAG 24 (Sujay *et al., 2012;* Bera *et al.,* 2018*;* Kolekar *et al.,* 2017*).*

Abiotic Stress Tolerance: Drought, heat and salinity are major constraints in rainfed oilseeds system. QTL mapping studies in Indian mustard (*Brassica juncea*) using SSR markers have identified genomic regions associated with membrane stability and seed yield under salt stress, with some QTLs accounting for more than 50% of the phenotypic variance. Similarly, high-density SNP genotyping has resulted in the identification of candidate genes for drought tolerance at germination and seedling stages through recent GWAS studies which can be utilized as useful markers for breeding mustard for tribal hill areas where rainfall is erratic.

Enhancement of oil quality: Ratio of oleic to linoleic acid which dictates shelf life, nutritional value and marketability. The high-oleic trait in groundnut is controlled through a recessive FAD2B allele and conventional selection is very inefficient. Allele specific PCR markers for FAD2 have been successfully used to combine high oleic trait with rust and LLS resistance using marker-assisted backcrossing in elite varieties like Kadiri 6 (Janila *et al.,* 2016*;* Bera *et al.,* 2019*).*

Gene Pyramiding for Multiple Traits: Rust resistance, LLS resistance and high oleic acid content are controlled by different genomic regions and hence simultaneous marker-based screening enables breeders to develop multi-trait improved varieties much more efficiently than sequential phenotypic selection. This directly benefits tribal and smallholder farmers who require varieties which are tolerant to multiple stresses with good oil quality (Bera *et al.,* 2018, 2019*).*

Success stories

Crop	Objective	MAB tool used	Reference
Soyabean	SCN-resistant cultivars Hartwig and Manokin	SSR (Satt 309 and 163)	Anand, 1992
Canola	Double-zero canola	RFLP, SNP (FAE 1 gene)	Stefansson *et al.,* 1983; Barret *et al*., 1998
Sunflower	NuSun (mid-oleic) and high-oleic hybrid	SSR markers flanking	Messmer *et al.,* 1998
Groundnut	foliar-disease-resistant varieties ICGV 15083 (Girnar 4) and ICGV 15090 (Girnar 5	SSR-MABC (MQTL-8)	Pandey *et al.,* 2017

Marker Assisted Backcrossing – A Case Study

The generalised MABC scheme with a documented groundnut example is shown in Figure 2. SSR markers (GM1009, GM1536, GM2079 and associated loci) were used for foreground selection of rust/LLS resistance QTLs coupled with genome-wide SSR background selection to introgress disease resistance into the elite variety ICGV 00350 and recover >90 per cent of the recurrent parent genome in two to three backcross generations *(*Bera *et al.,* 2018*;* Sujay *et al.,* 2012*).*

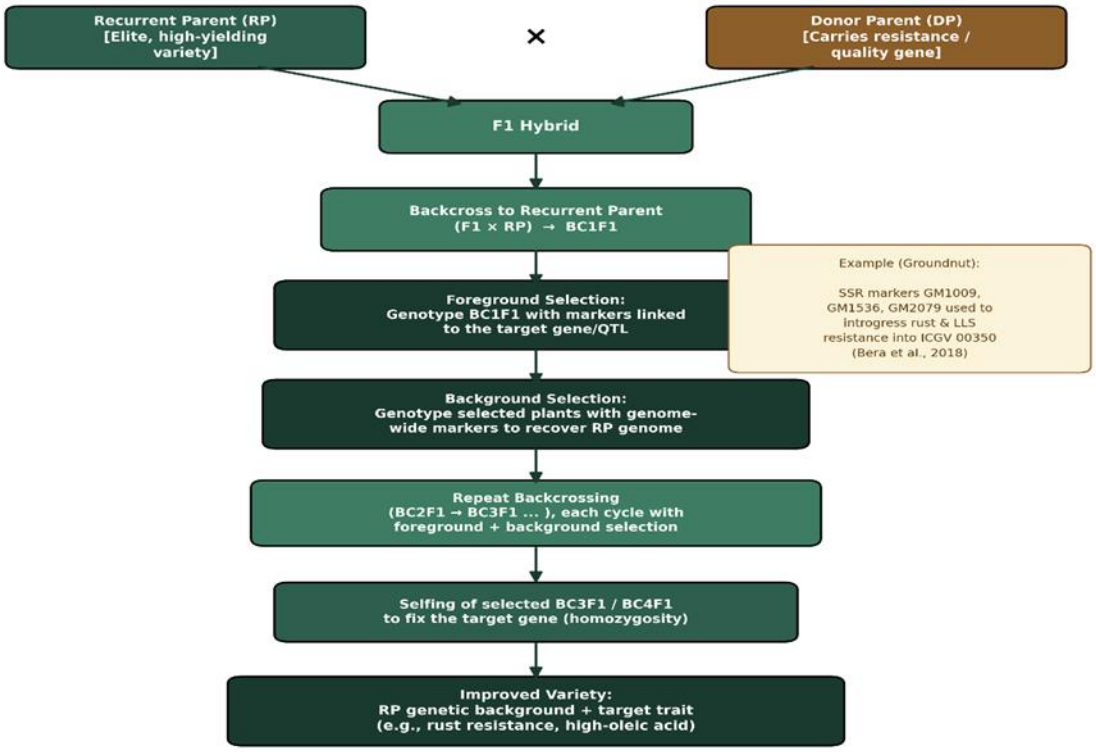


Figure 2. Marker-assisted backcross (MABC) breeding scheme for introgressing a resistance/quality trait into an elite oilseed variety, with a documented groundnut example.

Advantages of MAS over other breeding methods

Early generation, environment-independent selection: Marker genotypes can be scored at the seedling stage in the laboratory so that it is not necessary to grow plants to maturity or subject them to disease/stress conditions prior to selection, and genotype × environment interaction is not a source of selection error.

Detection of recessive and masked alleles: Some traits such as high-oleic acid content in groundnut (FAD2B, recessive) or disease resistance genes masked by epistasis cannot be detected reliably phenotypically in heterozygotes, but can be traced unambiguously at the DNA level.

Simultaneous selection for several traits (gene pyramiding): Many independent genes/QTLs can be followed in the same population in one generation whereas phenotypic selection would require many additional generations of backcross/selfing.

Reduced linkage drags: Background selection with genome-wide markers enables accurate detection and minimisation of unwanted donor parent DNA introgressed together with the target gene and helps to maintain the agronomic performance of the recurrent parent.

Shorter breeding cycle: Decisions on selection can be made earlier and more accurately, hence the number of breeding generations needed to fix a trait in an elite background is generally less than pedigree-based phenotypic backcrossing.

Improved accuracy of selection of low heritability and quantitative traits: Phenotypic selection for traits with low heritability or high environmental influence (*e.g*. drought tolerance components) is difficult, and marker assisted

selection anchored to validated QTLs increases the accuracy of selection for such traits.

Marker assisted backcrossing in tribal hill agro-ecosystems of oilseed crops

Stress Tolerance & Disease Resistance: MAB can be used to introgress genes for drought tolerance, cold tolerance and disease resistance (e.g. Alternaria blight in mustard, phyllody in sesame) into locally adapted varieties without changing the hill-adapted genetic background of the varieties and thus reducing the dependence on costly chemical inputs.

Shorter Breeding Cycles: Recovery of recurrent parent genome in conventional backcrossing takes 6-8 generations but MAB with background selection can do in 2-3 generations, a major advantage where growing seasons are short and limited.

Local Germplasm Conservation: Hill tribes are conserving useful oilseed landraces. MAB adds to these features one or two selected features but leaves the original genetic identity and cultural importance intact.

Quality & Adaptability Traits: MAB develops varieties with better quality (low glucosinolate, high oleic acid in mustard, high omega-3 in linseed, non-shattering capsules in sesame) and also traits suitable for Jhum based short cycle farming like early maturity.

Reduced Linkage Drag: It perfectly differentiates the foreground genes from the background genes which is often associated with undesirable genes in traditional breeding to obtain regular performance in hilly terrains.

Improving Community Seed Systems: Community seed banks help tribal farmers quickly identify, adopt and maintain MAB-improved varieties which are similar to local types with which they are familiar, improving local seed sovereignty and food security.

Limitations of Marker-Assisted Breeding

Yield Genetic Complexity: Selection based on individual markers is not efficient because hundreds to thousands of small effect QTLs control yield. Therefore, genomic selection is gradually replacing single-marker MAS for yield improvement.

QTL x Environment Interactions: Many QTLs are differentially expressed in different environments. Markers validated in one environment may not be predictive of the expression of the trait in another. There is a need for multi-environment QTL analysis and marker-environment interaction models.

Limited Reference Genomes for Some Oilseeds: While soybean and canola have high-quality reference genomes, crops such as sesame, linseed and some species of Arachis have limited or fragmented genomic resources, which limits marker development and GWAS.

High Ploidy in Some Oilseed Crops: Allotetraploid species such as B. napus (AACC genome, 2n=38) and tetraploid groundnut (AABB genome, 2n=40) lead to difficulties in marker development, QTL mapping and allelic discrimination owing to sub genome paralogs.

Cost and Infrastructure: Despite the drastic reduction in cost per marker, the infrastructure required for high-throughput genotyping pipelines still requires significant capital and bioinformatics expertise. These resources are still lacking in many breeding programs in developing countries.

Future Outlook

Speed Breeding integration: Integration of MAB with rapid generation advance (4-6 generations/year) in controlled environments in soybean, canola and groundnut to drastically compress breeding cycles

Haplotypes for breeding: From selection at single markers to haplotype blocks that capture multiple favourable alleles at the same time already being trialled in canola and soybean

Genomic Selection at scale: Integration of GS prediction models with high-density 50K-660K SNP platforms in public and private oilseed programmes worldwide

CRISPR-Cas9 and MAB: Combining gene editing of fatty acid pathway genes (FAD2, FAE1) with MAB for trait stacking – Calyxt's high-oleic soybean (Vistive Gold) is an early commercial example.

Climate-adaptive breeding: MAB targeting QTLs for heat, flood and drought adaptation identified through climate-informed GWAS in oilseed crops

Conclusion

Marker-Assisted Breeding is a precise, time-saving and ecologically sound strategy for crop improvement, most appropriate for the complex multi-stress situations of tribal hilly agro-ecosystems. MAB allows the precise introgression of desirable alleles from indigenous landraces and wild relatives to elite backgrounds, thus retaining the genetic legacy of tribal farming practices while improving yield, resilience and nutritional quality. Marker-Assisted Breeding has changed the face of oilseed crop improvement in the past three decades.

From double-zero canola, to SCN-resistant soybeans, drought tolerant groundnuts and high oleic sunflower hybrids, MAB has made measurable genetic gains that benefit billions of people – through better food, feed and oil quality, improved smallholder incomes and reduced reliance on agrochemicals.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine
Volume 04, Special Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-02

SPEED BREEDING: A FASTER WAY TO DEVELOP OILSEED VARIETIES FOR TRIBAL HILLY ECOSYSTEMS

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Introduction

Highly climate-vulnerable oilseed systems exist in the tribal hilly regions of India, the North-Eastern hill states, the Eastern Ghats and the Central Indian tribal belt. Rapeseed-mustard, soybean, sesame and niger are grown primarily under rainfed conditions on sloping and acid soils in short and increasingly unpredictable growing windows. There are also recurrent heat waves, late monsoon onsets and irregular monsoon withdrawals, which further reduce the available window for crops to grow. Conventional breeding takes 8-10 years or longer from the time of hybridisation to the time a farmer can use the crop, and is appropriate for a stable climate but not for changing target environments within the programme's lifetime. Breeders have a need for a tool that allows them to breed faster without compromising genetic gain. One such approach is speed breeding, which is now being used in combination with marker-assisted and genomic approaches to speed up the delivery of climate-resilient oilseed varieties (Watson *et al.*, 2018; Hickey *et al.*, 2019).

What Is Speed Breeding?

Speed breeding (SB) is a method of reducing the generation time of a plant (seed-to-viable seed) under controlled conditions, without altering the genome of the plant. It takes advantage of the fact that major crops (wheat, barley, chickpea, pea, canola/mustard, soybean) adjust their transition from vegetative growth to flowering in response to photoperiod (day length), light quality and temperature. Flowering and seed-maturation signals can be induced earlier than under field or standard glasshouse conditions by artificially extending the photoperiod, optimising the light spectrum and fine tuning the temperature (Watson *et al.*, 2018; Ghosh *et al.*, 2018).

Importantly, speed breeding does not change the DNA of plants. It can be used in conjunction with, and sometimes in combination with, conventional breeding, marker-assisted selection, genomic selection, mutation breeding and genome editing. SB speeds up the step in the breeding pipeline that is common to almost every pipeline, the generation-advancement step. It is a tool that can be used to enhance breeding strategy, not to replace it.

The Science behind Speed Breeding

Photoperiod Extension

In the case of long-day and day-neutral crops (wheat, barley, chickpea, pea, canola/Brassica), they flower earlier when exposed to extended daily light (usually 16–22 hours). Under controlled temperature, a 22-hour photoperiod resulted in up to six generations per year for spring wheat, barley, chickpea, and pea, and four generations per year for canola, compared to only two to three generations in standard glasshouse conditions (Watson *et al.*, 2018).

In contrast, short-day crops such as soybean react in a negative manner to continuous long-day light, as they are delayed in flowering by

the lack of days of darkness below a threshold. To overcome this, Jähne and colleagues used a blue-enriched, far-red-deprived spectrum and a 10-hour photoperiod for soybean, rice and amaranth, allowing up to five generations per year for soybean (Jähne *et al.*, 2020). For soybeans, the approach involves providing a 22-hour photoperiod after the start of flowering, which accelerates the rate of pod fill and maturation, but does not shorten the time to flowering and achieving up to six generations per year (Aciksoz *et al.*, 2025).

Light Quality and Intensity:

LED arrays allow for the precise control of light intensity and spectrum, particularly the red: far-red and blue-light ratios that control pathways of flowering through phytochromes and cryptochromes, respectively. Adjusting these ratios is crucial to customize protocols for specific crops or maturity groups (Jähne *et al.*, 2020; Song *et al.*, 2022).

Temperature and Vernalisation Management

Optimum temperature is maintained between day and night to prevent heat or cold stress and to ensure maximum vegetative growth. For winter-type cereals and oilseeds that require vernalisation, a short cold period of germinated seedlings is applied, rather than a natural winter (Song *et al.*, 2022).

Early Harvest and Immature Seed Germination:

To maximize seed output, speed breeding harvests seed 2-3 weeks after flowering and either subject the seed to controlled desiccation or germinate fresh seed to establish the next generation.

This alone is enough to save a few weeks per cycle and is vital to the overall time saving aspect of speed breeding (Ghosh *et al.*, 2018; Fang *et al.*, 2021).

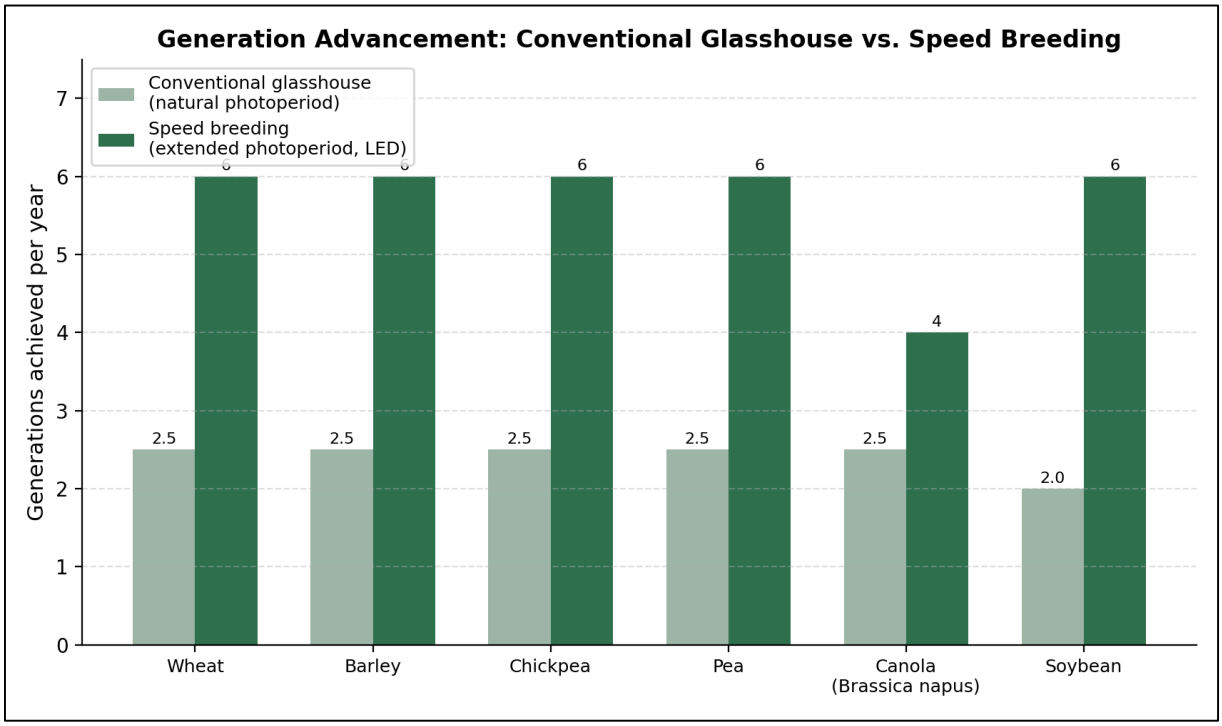


Figure 1. Generation advancement achieved under conventional glasshouse conditions versus speed breeding, for crops with validated protocols.

Set up of a Speed Breeding Protocol

A typical speed breeding system, whether it is a dedicated growth chamber or a glasshouse fitted with supplemental LED lighting, includes four components: a longer and spectrally optimized photoperiod, controlled temperature and humidity, a high-density planting design to achieve maximum output per area, and early harvest with assisted germination of immature seed. General arrangement is shown in figure 2.

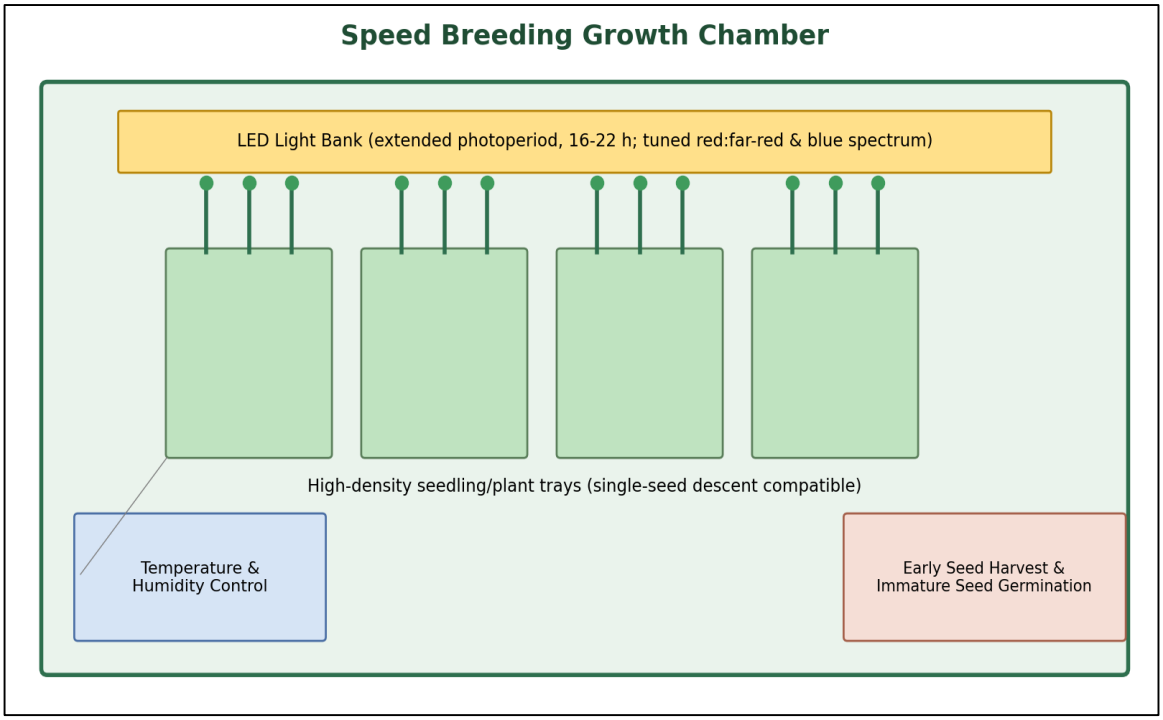


Figure 2. Schematic layout of a typical speed breeding growth chamber

One seed per plant is usually used in these situations, with populations advanced by the single-seed descent (SSD) method, which allows for the rapid fixation of homozygous lines while requiring minimal space and labour. Low-cost variants of these chambers, built from modified shipping containers or insulated cabinets fitted with commercial LED arrays and are particularly relevant for resource-limited regional research stations (Ghosh *et al.*, 2018).

Application to Oilseed Crops

Rapeseed-Mustard (*Brassica* species)

Indian mustard (*Brassica juncea*) is a long-day species related to canola, and is expected to be highly amenable to the same speed breeding principles that have been validated for *Brassica napus*: extended sixteen- to twenty-two-hour photoperiods along with controlled temperature, resulting in up to four generations per year, and up to 6.5 generations per year under more intensive 'comprehensive speed breeding' protocols involving vernalisation of germinated seed and high-density hydroponic seedling culture (Song *et al.*, 2022).

Soybean

Soybean is a short-day oilseed and needs a different approach. A ten-hour photoperiod with a blue-enriched, far-red-deprived LED spectrum has resulted in up to five generations per year (Jähne *et al.*, 2020), and a photoperiod of twenty-two hours, applied only after flowering

has begun, together with an immature-seed germination technique, has yielded up to six generations per year, with noticeably improved seed viability (Aciksoz *et al.*, 2025).

A complementary off-site nursery and fresh-seeding approach combining marker-assisted selection has also shown at least four generations per year in largely natural conditions in China, demonstrating that speed breeding does not always require the use of energy-intensive chambers (Fang *et al.*, 2021).

Sesame and Niger

Sesame (*Sesamum indicum*) and niger (*Guizotia abyssinica*) are two crops that are agronomically and nutritionally important crops in tribal hilly cropping systems and are relatively under-researched in terms of speed breeding.

Both are warm season crops, broadly day neutral/short day, and the principles of photoperiod and light quality established in soybean, rice and amaranth (Jähne *et al.*, 2020) would be a reasonable starting point and could be adapted and validated by regional research institutions without having to develop protocols from first principles.

Integration with other breeding tools

The best time to speed breed is when modern tools are used. With DNA markers, scientists can test young plants, and only grow the best ones further, saving even more time and space.

When marker testing or GP is used in conjunction with speed breeding, time to develop a new variety can be reduced from approximately 9–10 years to 3–4 years (Figure 3) (Fang *et al.*, 2021; Hickey *et al.*, 2019).

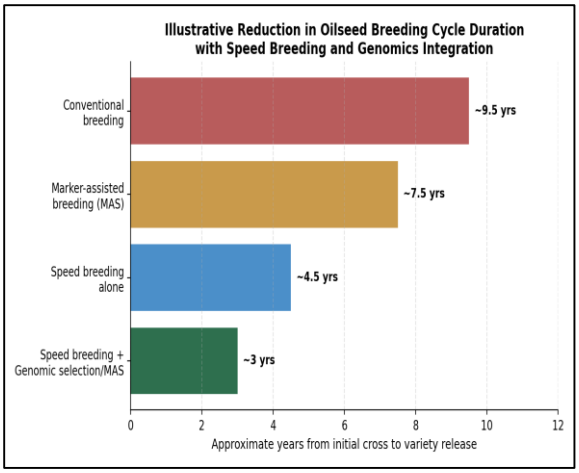


Figure 3. Illustrative comparison of typical variety-development timelines.

Relevance to Tribal Hilly Ecosystems

- Season independent breeding: Hilly areas may only have one crop season per year. One of the advantages of speed breeding is that it can be conducted in indoor conditions, meaning it is not weather or seasonal dependent.
- Quick response to new stresses: If a new pest or disease, such as aphids or *Sclerotinia* on mustard occurs, it can be addressed quickly by breeding resistant plants earlier
- Useful traits such as tolerance to acidic soil are available in the indigenous germplasm of mustard, sesame and niger. This is because the traits are more rapidly incorporated into new varieties of plants through speed breeding.
- Synergy with participatory varietal selection: New varieties go to farmers' field for testing earlier, thus accelerating the entire process from idea to harvest.

Advantages and Limitations

Advantages	Challenges / Limitations
Up to 2–3 times more generations per year than standard glasshouse conditions	High upfront infrastructure and energy cost for LED chambers
Season- and location-independent breeding, valuable for short hill growing windows	Genotype- and species-specific responses; protocols must be optimised per crop
Fully compatible with MAS, genomic selection, mutation breeding and genome editing	Limited published protocols so far for mustard, sesame and niger specifically
Enables rapid pre-breeding using indigenous tribal landraces	Requires trained personnel and reliable power supply for continuous chamber operation
Compatible with low-cost cabinet designs for resource-limited stations	Cannot replace multi-location field testing or participatory on-farm evaluation

Way Forward for Tribal Hilly Oilseed Breeding Programmes

- Create and test specific speed breeding protocols for Indian mustard, sesame and niger, along with the ones developed for canola and soybean.
- Facilitate low cost, regionally appropriate speed breeding cabinets in ICAR/State Agricultural University and KVK Research stations for tribal hilly belts with a focus on energy efficient LED systems that can be used in areas with unreliable power supply.
- Combine speed breeding, marker-assisted and genomic selection pipelines that are under development for stress tolerance in oilseeds to allow for the greatest amount of time saved per breeding cycle.
- Utilize speed breeding for the purpose of making fast pre-breeding with indigenous tribal landraces with valuable local stress tolerance alleles reaching usable breeding lines sooner.
- Ensure close connections with multi-location field trials and participatory varietal selection to ensure proper validation of speed-bred lines in the context of actual hill agro-climatic conditions prior to release.

Conclusion

What speed breeding does do is to shorten up the section of the breeding pipeline that is usually the longest in calendar time - the breeder's judgment, indigenous knowledge and rigorous field validation. In the case of tribal hilly oilseed production system with short growing seasons and growing climate stress, this compression is not a luxury, but a more pressing need. When used in combination with marker-assisted and genomic tools, and supported by the extensive native germplasm found in these areas, speed breeding is a scientifically sound approach to provide climate-resilient varieties of mustard, soybean, sesame, and niger - a far cry from years behind the climate curve.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine
Volume 04, Special Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-03

YELLOW REVOLUTION 2.0: BREEDING MUSTARD FOR TOUGH TERRAINS

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Introduction

India's first Yellow Revolution was launched in the 1980s which transformed oilseed farming on the fertile plains of Rajasthan, Haryana, and Uttar Pradesh. It briefly turned the country into a net exporter of edible oil by 1989-90 but this trend was not sustainable and, within a decade, India was back on the importation treadmill with over 50% of edible oil imports, and is still doing so. That revolution came for flat land irrigated by water and failed to make it into the tribal hills where farming resembles nothing like the plains. Now the question arises that whether the next Yellow Revolution can rise new breeds the mustard seed that will withstand the rain, the drought, and the nutrient poor soil of hills? If the first revolution aimed for higher yield, this one must build resilience precisely where conditions are not suitable.

Why Tribal Hills Need Their Own Mustard Revolution

Most of the mustard varieties developed over the last few decades were bred and tested on well-irrigated, fertile soil of research stations. There they perform very well. However, tribal hill ecosystems are a completely different place with the following characteristics:

- Land sloping away from the crops before they can use the water.
- No irrigation as backup to rainfed conditions.
- Loss of topsoil and nutrients through soil erosion during monsoon
- Moisture stress occurs during critical growth stages
- Poorly nourished and often acidic soils
- Climate uncertainty such as delayed monsoons, sudden heat surge, unseasonal rain *etc.*

A variety that is good for irrigated fields in Punjab could not do as well on a rain-fed tribal hillside. Climate resilience for hills is not same as the plains; it has to be developed specifically for the hilly conditions.

Mustard: Not only an oilseed

Mustard (*Brassica juncea*) is often treated just as a simple condiment crop, but its importance is more than that: it is one of India's three major oilseeds with soyabean and groundnut making up over 90% of the national oilseeds production. It is an important livelihood crop in lean period for small farmers, an important support crop for honeybee population and a good fit for rain fed crops after kharif crops on residual moisture.

This is important as over 50% of India's edible oil needs are still met through imports. With an investment of Rs 10,103 crore (2024-25 to 2030-31), the government's NMEO-OS mission is focused on boosting oilseed production to nearly 70 million tonnes from around 39 million

tonnes, with mustard being an important component.

The case is further enhanced by the yield-gap data: India's average yield of mustard is 1,414 kg/ha, which is still significantly lower than the best performing state (1,921 kg/ha) and a mere 28% increase in production would be possible without an increase in the area. Just when these varieties are supposed to grab the opportunity for climate resilience and rain-fed suitability.

What Does A "Future-Ready" Mustard Plant Look Like?

It is useful to visualize the goal for future breeding programmes for the tribal hill environment - the ideal mustard. It is useful to imagine the ideal mustard that future breeding programmes are striving to achieve for tribal hill conditions, before exploring how they are achieved.

The ideal mustard plant for tribal hills

i. Drought-tolerant: withstands prolonged dry periods with little loss of yield
ii. Heat tolerant: Tolerant of rapid temperature changes, particularly during flowering.
iii. Early maturing: finishes its life cycle before the moisture is depleted.
iv. Tolerant of drought conditions: requires less water to grow than other crops
v. Disease resistant: especially to white rust and Alternaria blight
vi. Pest tolerant: less reliance on expensive pesticide sprays
vii. Economically viable for smallholders: high oil yielding
viii. Appropriate for rain-fed agriculture: no need for assured irrigation
ix. Tolerant of slopes and deep moisture: firmly anchored on slopes and absorbs moisture deeply
x. Consistently performs over time, across environments

Science behind a Stronger Mustard

It is not a single technique that is used to develop such a plant. It requires an entire toolbox of breeding methods, ranging from traditional field practices to the most modern genomic and gene-editing technologies. The different breeding techniques used are as follows;

A. Conventional Breeding

Traditional methods include: Mass Selection (Several plants are selected on the basis of their phenotype), Pure Line Selection (Isolation of pureline from a mixture of purelines), Hybridization (Mating between two different strains), Pedigree Method (Individual plants are selected in F_2 and the subsequent generations and a pedigree record is maintained), Bulk Method (Natural selection is done for some generations and in the end pureline varieties are developed through individual plant selection), and Backcross Breeding (Repeated backcrossing of the F_1 and subsequent generations to the recurrent parent).

B. Heterosis Breeding / Hybrid Vigour

Superiority of F_1 over the parents. This is mainly based on Cytoplasmic Male Sterility (CMS) systems for controlled cross-pollination. For the first time in India, the commercial hybrid DMH-1 has been developed by using the Indian and East

European gene pools to make use of this effect. Breeders continue improving CMS-restorer systems (e.g., Ogura CMS) via marker-assisted selection.

C. Mutation, Wide Hybridization & Marker Tools

Mutation breeding: Breeding method utilizes mutagens like gamma rays, X-rays, or chemical mutagen to create variations. It helps in developing traits like early-maturing and disease-resistant lines with improved plant architecture. Ex: Gamma-irradiated mutants mature 2-3 weeks early with better oil content; ICAR-CSSRI Karnal developed salt-tolerant CS-series mustard via mutation breeding.

Wide hybridization: Cross between two species of the same genus or of different genera. Ex: B. *rapa* × B. *nigra* crosses yielded 33 synthetic B. *juncea* lines, varieties JM-1, JM-2, DMH-1 and Basanti had acquired white-rust resistance by introgression with B. *carinata*/ B. *napus*.

Doubled haploid (DH) technology: This reduces the time required to establish a stable line normally taking 8-10 years to just one step involving doubling of chromosomes. DH populations have also been used for mapping hundreds of yields related genetic regions in Brassica juncea. The white-rust resistance gene was mapped by Ex: Tumida × Varuna DH population and another gene was mapped by Varuna × Heera DH population.

Marker-assisted breeding: It employs DNA markers as genomic signposts to allow breeders to ensure a gene for disease resistance, stress tolerance, or oil quality before a seedling matures and pass it on in a precise manner to elite varieties. Ex: Markers WR2/WR3 are flanking the $Ac2^{1}$ white-rust gene which was used to backcross resistance into variety NRCDR-601 with a minimal yield loss.

D. Genomics & Digital Tools

Genomic selection: It uses genome-wide DNA markers to predict the performance of plants before field testing. It is very useful for more complex, multi-gene traits such as resistance to drought.

Genome-Wide Association Studies (GWAS): It use natural genetic diversity to link specific phenotypic traits (e.g., yield, disease resistance) with genetic markers across the whole genome. One recent study screened 193 *Brassica juncea* accessions under drought stress, and GWAS was combined with gene-expression analysis to identify specific genes that react to drought stress.

Pangenomics: It is the study of the entire gene repertoire of a species, rather than just a single individual's genome. this approach helps breeders identify vital traits such as disease resistance, drought tolerance, and higher yield that were lost during centuries of domestication but still survive in wild relatives.

Speed breeding: This method manipulates environmental conditions such as light spectrum, photoperiod, temperature, and humidity to drastically shorten the seed-to-seed cycle of plants. It potentially compresses breeding timeline from 8-10 years to just 3-5 years.

High-throughput phenotyping: combining robotics, sensors, and AI to measure thousands of physical and physiological traits non-destructively.

AI/machine learning: It is increasingly being used to predict better crosses and future variety performance under various climate scenarios.

E. Gene Editing (CRISPR-Cas)

The most advanced tool is a tool that allows for very targeted editing, without introducing unwanted genetic baggage. The polyploidy genome of mustard, however, is more complicated than simpler crops and most successes have been achieved in related species, not commercial mustard. An area that has the potential for success but still under development stage.

Exploring the Diversity of Indigenous Mustard

One resource which is largely underestimated is the one which is there silently in the field of the tribal farmers. The locally grown mustards might have the very genes the breeding programs are searching for and the wild relatives of mustards on the edges of fields may have them as well. There are numerous drought-tolerant, salt-tolerant and cold-tolerant lines recorded in the inventory of plants which are resilient to climate change.

Root Systems and Crop Resilience

Roots are often the most ignored trait in breeding, simply because we can't easily see or measure them. However, in hill farming root system may be as important as above-ground activities. Deeper root systems will be able to extract moisture from the soils that were not consumed during dry periods, and will absorb water more efficiently, and nutrients more efficiently from old and poor hill soils.

In response to drought stress, mustard's gene expression changes significantly in its ability to transport nitrogen, and there is a significant correlation between the changes in the genes' expression and drought tolerance. Therefore, breeding for deeper, stronger roots are very important for building resilient mustard plant.

Breeding for Higher Bee Pollination

Pollinated mainly by insects, it is one of the most beneficial of the farming enterprises because of its association with the bees. It has been proven that honeybee pollination could improve yield, pods per plant and seeds per pod. Yields were approximately 15% greater in plots where bees were allowed to pollinate than in those plots in which bees were excluded, in one study.

In another investigation it was found that the insect pollination of mustard resulted in an increase in yield of approximately 200 per cent compared with the unpollinated, and that the pollination also brought about uniformity and earlier maturity of pod set.

During the surveys, over a dozen species of various honeybee species were recorded visiting mustard flowers with honeybee visits to mustard flowers being the highest in all areas of mustard cultivation in Punjab.

Importance

i. Bee attractiveness of a flower is based on its features like nectar amount, flowering time and colour
ii. Better and more consistent pollination and yields are associated with more attractive flowers.
iii. Wildlife and biodiversity in general are found in pollinator friendly fields.

Smart Farming with Good Genetics

Good genetics must be combined with smart farming for real resilience in tribal hill farming: Precision farming should be used to carefully manage water and nutrients on small sloped farms. The drones and satellites to keep track of the stress on spread-out farms.

Weather forecasting for farmers' use to help them adapt their sowing to the unpredictable rains. Advice for farmers based on information technology in their own language, relevant to their context.

For example, a Krishi Vigyan Kendra (KVK) project in Bokaro district of Jharkhand organized on field demonstrations and trainings for tribal farmers on improved technology for mustard cultivation including visits to the research station of DRMR.

It proves that good genetics coupled with good support/training should get to the hill and tribal communities. There may be problems that cannot be solved by genetics.

Conclusion

What will the tribal hills of the Indian look like 100 years after Independence in 2047 in a golden mustard field and fields which were deemed too poor or too steep? The new varieties brought by genomics and AI grow in a changing climate, while traditional varieties do not; The farmers in the hills turn into entrepreneurs of the seeds, import of edible oil decreases and pollinator friendly varieties of deep root crops make the hills sustainable. The first Yellow Revolution led to an increase in production. The next one needs to be resilient, combining traditional knowledge and modern breeding with climate-smart farming to ensure mustard's success in the face of adversity, and in the midst of opportunity

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine

Volume 04, Special Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-04

WATER MANAGEMENT IN OILSEED CROPS: A KEY TO SUSTAINABLE PRODUCTION AND WATER SECURITY

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Abstract

Oilseed crops like groundnut, soybean, rapeseed-mustard, sunflower, sesame, safflower, castor and linseed play a significant role in food security, nutritional security, industrial raw material, livestock feed, and in the biofuel industries, as they are directly contributing to the production of edible oil. But the challenges to sustainable oilseed production are vast due to the increase in water scarcity, irregular rainfall, depletion of the ground water, and climate change. While many oilseed crops are fairly drought tolerant, their yield and the quality of the oil produced is very sensitive to moisture stress during critical stages of growth, including flowering, pod development, seed filling, and oil accumulation. Therefore, efficient water use is critical for enhancing crop productivity and water-use efficiency.

The importance of water in oilseed production, water needs of oilseeds and periods of critical water use are emphasized. It covers modern methods of water management such as irrigation scheduling, deficit irrigation, micro-irrigation system and precision water management technologies. The contribution of agronomic measures like mulching, conservation tillage, rainwater harvesting, diversification, and soil health management to soil water conservation and improving water-use efficiency is also highlighted. Moreover, the article discusses the impacts of climate change and considers future actions like breeding drought-resistant crops, implementing new irrigation techniques and improving watershed management initiatives. Water productivity can be greatly increased by adopting scientific and water-efficient management practices, which can also increase oilseed production and sustain production under varying climatic conditions. Water management will be a key factor in ensuring sustainable oilseed production, food security, and the environment in the future.

Key words: Irrigation scheduling, deficit irrigation, micro-irrigation, water-use efficiency, climate change, moisture conservation

Introduction

Oilseed crops are an important part of the global agricultural stage, both for food and nutrition, and for industry. Major oilseed crops like groundnut (*Arachis hypogaea*), soybean (*Glycine max*), rapeseed-mustard (Brassica spp), sunflower (*Helianthus annuus*), sesame (*Sesamum indicum*), safflower (*Carthamus tinctorius*), castor (*Ricinus communis*), and linseed (*Linum usitatissimum*) provide edible oils, protein and industrial raw materials, livestock feed, and biofuel feedstock. Vegetable oils are a significant source of human dietary energy in the world and are also increasingly being used in pharmaceutical, cosmetic and renewable energy industries (FAO, 2023). Oilseed crops are grown in almost 27 million hectares in India and are the second largest agricultural commodity group after cereals. India, though one of the highest producers and consumers of oilseeds, has lower

productivity as compared to many developed agricultural systems, mainly due to abiotic stresses especially water scarcity and inefficient water management practices (Directorate of Oilseeds Development, 2023).

Water is one of the most important inputs that can affect the growth, development and yield formation of oilseed crops. Apart from this, several oilseed crops, which are relatively drought tolerant, are mostly irrigated, but their productivity is very sensitive to moisture stress during the flowering to pod formation stage, pod development to seed setting stage, and seed development to oil accumulation stage (Farooq *et al*., 2017). The limited supply of water in these stages can significantly lower photosynthetic activity, nutrient absorption, reproductive success and yield losses. However, over-irrigated plants can result in water logging, loss of nutrients, disease infection and loss of seed quality and oil content (Pereira *et al*., 2020). Hence, it is important to balance the supply and demand of water to crops for maximizing the productivity and efficiency of resources used.

In recent years, water management in oilseed production has become a greater challenge with increased pressure on freshwater resources. Variability in rainfall frequency and intensity, more drought and heat stress, falling groundwater levels, and increased demand for water from urban and industrial uses are making water scarcer in many agricultural regions in the context of climate change (IPCC, 2022). Nowadays, agriculture consumes almost 70% of global water withdrawals, underlining the importance of implementing more efficient water management strategies (FAO, 2021). India is highly dependent on monsoon rains for the production of oilseeds and irregular rainfall and extended dry periods often lead to unreliable produce and poor farm profitability.

There are many opportunities to optimise oilseed production with efficient water management practices, and to conserve scarce water resources. Irrigation scheduling using crop evapotranspiration, soil moisture monitoring and critical growth stages can significantly improve water-use efficiency and crop performance (Jones, 2004). Moreover, the modern technologies like drip irrigation, sprinkler system, deficit irrigation, precision agriculture technologies, and remote sensing-based water management has shown significant potential to enhance productivity and water productivity (Gu *et al*., 2020). Other agronomic practices like mulching, conservation tillage, rainwater harvesting and integrated nutrient management (INM) also enhance soil moisture retention and drought resistance.

With the rise in demand for edible oils and water scarcity, water sustainable management has become an important part of oilseed production systems. The use of water-saving technologies and climate-friendly farming methods will not only support productivity and profitability of agricultural production, but also help to ensure long-term environmental sustainability and food security. Hence, the principles and practices of water management in oilseed crops is a very important aspect for the researchers, policy makers, extension services personnel and farmers aiming to attain sustainable agricultural development.

Importance of Water in Oilseed Production

Water is one of the essential factors for plant growth and production and is important for determining the productivity and quality of oilseed crops. It plays a role in almost all the physiological and biochemical functions such as seed germination, nutrient uptake, photosynthesis, cell growth, flowering, seed production, and oil biosynthesis (Farooq *et al*.,

2017). Oilseed crops are water stressed at specific growth phases and are less water demanding than major cereal crops like rice and sugarcane. Therefore, effective water management is critical for higher yields and good oil quality and to support sustainable production systems.

Ensuring soil moisture is sufficient for good root development and for uptake and translocation of soil nutrients to various plant parts. Water is also used as a medium for metabolic activities and to maintain plant turgidity required for cell division and expansion. When moisture is inadequate, photosynthetic activity is decreased, nutrient uptake is limited, reduced leaf senescence leads to a reduction in biomass and seed yield (Pereira *et al*., 2020). Water stress, especially during the reproductive phase of seed oilseed crops, is detrimental since it will affect the viability of pollen, the fertilization rate, oil setting, and the accumulation of oil. It has been observed that drought stress during flowering and filling stage can severely decrease the number of pods in groundnut, siliqua production in mustard and grain filling in sunflower and soybean (Farooq *et al*., 2017).

Too much water is as bad as not enough water, and too little can have the same effect as too much. Excessive watering is likely to result in water logging, shallow soil roots, nutrient loss, and higher cancer rates of fungal diseases. These conditions have a negative impact on root development, and may result in lower nutrient-use efficiency, which in turn creates less productivity and seed quality. This modern approach to water management is not just about water alone, but about the appropriate quantity of water in the optimal growth stage and most efficient way to deliver it (Jones, 2004).

The research has shown that irrigation scheduling based on crop evapotranspiration (ET), soil moisture status and climatic demand play significant roles in crop water productivity. Evapotranspiration is a combined loss of water, from evaporation by soil and transpiration by crop and is considered as an important indicator of crop water requirement. Irrigation scheduling is essential for water use efficiency, and by using ET and critical growth stages, it can help to achieve better results with the goal of producing more crop per drop (Gu *et al*., 2020).

Water Requirements of Major Oilseed Crops

Oilseed crops have wide range of water needs depending on species, length of crop, climate, soil, and management. Traditionally, one of the most popular oilseed crops, groundnut needs between 500 and 700 mm of water throughout its life cycle. Moisture stress is critical during the flowering, pegging and pod development stages and irrigation during these critical stages can enhance pod production and kernel quality (Aiken *et al*., 2011).

The water requirements of rapsed-mustard are relatively low (250 to 450 mm) with particular emphasis on moisture availability during flowering and siliqua development for a higher seed yield and oil content. Likewise, sunflower needs 450-700 mm of water and supplemental irrigation is beneficial during flowering and grain filling stages. During such times, water stress may significantly affect the size of seeds and the amount of oil stored (Hussain *et al*., 2018).

Soybean is another important oilseed crop that will need 450-800 mm of water depending on environmental conditions and cultivar characteristics. It is recommended to irrigate during flowering and pod-filling stages because water shortage at these times will result in flower drop and poor seed development. Linseed and safflower are relatively drought resistant crops which can yield reasonably under short of optimum moisture supply conditions.

However, irrigation at flowering and seed-filling stages has been proven to have a substantial impact on productivity and oil yield.

The seasonal ET of oilseed crops is generally in the range of 300 – 800 mm depending on the oilseed and climatic conditions and management practices (Pereira *et al*., 2020). Hence, knowledge of the water use efficiency and incorporation of efficient irrigation method is crucial for enhancing water productivity, maintaining oilseed production and ensuring agricultural resilience in the changing climatic conditions. Modern Approaches to Water Management

Modern Approaches to Water Management in Oilseed Crops

Irrigation Scheduling

Irrigation scheduling is the determination of the best time and amount of water irrigation to plants. Traditional, based on a fixed time schedule irrigation can cause over-irrigation or water stress. The modern scheduling methods involve using crop evapotranspiration (ET) and soil moisture analysis, weather forecasting, and crop growth models to enhance water efficiency and water productivity (Jones, 2004; Gu *et al*., 2020). Correct timing of watering allows water to be applied to meet crop needs, minimising wastage and improving yields.

Deficit Irrigation

Deficit irrigation is one of the water-saving techniques, in which the water requirement is reduced in sensitive growth stages and kept at a satisfactory level in critical reproductive stages. This will benefit water use efficiency and enable farmers to save water without significant decreases in yield. In some oilseed crops, deficit irrigation has proven to be successful, especially in water-limited and semi-arid areas (Fereres & Soriano, 2007).

Micro-Irrigation Systems

Micro-irrigation is becoming popular in oilseed because of its high efficiency which includes drip irrigation and sprinkler irrigation. These systems bring water right to the root zone, which reduces losses from evaporation, runoff and deep percolation. Micro-irrigation has been proven to reduce water use by 30–50%, increase nutrient-use efficiency and crop productivity (Pereira *et al*., 2020). In groundnut, sunflower and castor, drip irrigation has proved to be very effective.

Precision Water Management

The recent developments of digital agriculture have facilitated precision water management by means of soil moisture sensors, remote sensing, satellite images, drone and decision-support systems. Such technologies enable the real-time monitoring of soil water status, crop stress, and weather conditions, empowering farmers to make informed irrigation decisions and enhance water-use efficiency (Gu *et al*., 2020).

Water use efficiency in the production of oilseed crops.

Water management is not just about irrigation management, and there are a number of agronomic strategies that can be implemented to help conserve soil moisture and drought conditions.

Mulching

Crop residue mulch, organic mulch, plastic mulch can help to reduce soil evaporation, control soil temperature, weed control and improve water use efficiency. It also enhances the health of soils and supports growth of crops in water-limited environments (FAO, 2021).

Conservation Tillage

Conservation tillage systems, such as reduced tillage and residue retention, enhance

soil structure, encourage more water percolation and minimize runoff losses. These practices are responsible for sustaining the soil moisture for longer time and also aid in sustainable production of crops (Farooq *et al*., 2017).

Rainwater Harvesting

These water collecting facilities like farm ponds, check dams, water storage reservoirs harness excess rainfall for use when there is a drought. These interventions are especially useful in rainfed oilseed growing areas (FAO, 2021).

Crop Diversification and Soil Health Management

Under water limiting conditions, intercropping oilseeds with cereals or legumes can increase the utilization of resources and the resilience of the system. Similarly, when the organic manures, compost and biochar are applied it leads to the rise in soil organic matter content, water holding capacity and drought tolerance (Farooq *et al*., 2017).

The growing threat of climate change and the impact of future challenges.

The IPCC predicts that droughts, heatwaves and unpredictable rainfall will become more common and more severe under a changing climate in the future, creating a serious problem for oilseed production around the world (IPCC, 2022). Development of drought resistant varieties, implementation of micro-irrigation technologies, integration of weather based advisory services, agricultural practices that are suitable for climate and weather and enhance watershed management programmes should thus be become a priority for future water management strategies. Incorporating better cultivars, innovations in irrigation and sustainable agronomic practices will play a key role in improving oilseed system resilience and productivity in the face of changing climate.

Conclusion

Water management decisions have an important role to play in the productivity, profitability and sustainability of oilseed crops. There are several water-use efficient practices that can be adopted to increase water-use efficiency and crop production, such as scientific irrigation scheduling, deficit irrigation, micro-irrigation systems, soil moisture conservation practices, etc. To secure future oilseed production, food security and environmental sustainability, the implementation of water-smart technologies and climate-resilient management practices will be critical as fresh water resources continue to become scarce due to the competing demands and climate change.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine

Volume 04, Special Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-05

TRANSFORMING MUSTARD CULTIVATION IN TRIBAL HILLS THROUGH THE SYSTEM OF MUSTARD INTENSIFICATION

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Introduction

Oilseed crops play a crucial role in global agriculture by providing edible oils, nutritional security, industrial raw materials, and livelihood opportunities. Over the past three decades, global oilseed production has grown at an annual rate of about 4.1%, making it one of the fastest-growing agricultural sectors. Despite being the world's fourth-largest edible oil economy after the United States, China, and Brazil, India continues to face a significant gap between domestic production and consumption, resulting in heavy dependence on edible oil imports. Among the oilseed crops, rapeseed-mustard occupies a prominent position, contributing nearly 27.8% of the country's oilseed economy and accounting for about 35% of total oilseed production. The crop is grown on approximately 7.99 million hectares with a production of around 11.9 million tonnes and an average productivity of 1,497 kg ha^{-1} (Mahto *et al*., 2024). Mustard (*Brassica juncea* L.) is valued for its high oil (40-45%) and protein (20–25%) content and serves as an important source of edible oil, livestock feed, and industrial products.

However, mustard productivity remains below its potential due to poor crop establishment, delayed sowing, inadequate plant population, nutrient deficiencies, and inefficient resource utilization, particularly in tribal and hilly agro-ecosystems where farming is largely rainfed and resource-constrained. To address these challenges, the System of Mustard Intensification (SMI) has emerged as a promising production approach inspired by the principles of the System of Rice Intensification (SRI).

SMI focuses on healthy seedlings, optimum transplanting age, wider spacing, enhanced root development, and efficient nutrient and water management to maximize the productivity of individual plants. Research by Sushma *et al*. (2023) showed that transplanting 25-day-old seedlings at wider spacing (60 × 60 cm) significantly increased branching, siliqua formation, and seeds per siliqua, while Mahto *et al*. (2024) reported seed yields exceeding 2.0 t ha^{-1} with higher net returns and benefit-cost ratios under SMI.

Furthermore, integrated practices such as ridge sowing, sulphur application, and mulching have been shown to improve crop growth and productivity, complementing SMI principles and promoting sustainable intensification of mustard cultivation (Sharma *et al*., 2025).

Therefore, SMI offers a viable pathway for enhancing mustard productivity, profitability, resource-use efficiency, and sustainability, particularly in tribal and hilly farming systems.

System of Mustard Intensification (SMI): An Overview

The SMI is an innovative crop management approach developed on the principles of the SRI to enhance mustard productivity through efficient use of resources. Unlike conventional cultivation, which relies on direct sowing with high seed rates and dense plant populations, SMI emphasizes transplanting young seedlings, maintaining optimum plant spacing, improving root growth, and adopting scientific nutrient and water management practices. The primary objective of SMI is to maximize the productivity of individual plants while reducing seed requirement and increasing resource-use efficiency. Studies have reported seed yields of 3.0-5.7 t ha^{-1} under SMI compared to about 1.0-1.5 t ha^{-1} under conventional cultivation, highlighting its potential for improving mustard production and profitability (Patra *et al*., 2023; Mahto *et al*., 2024).

Major Components of SMI

Nursery Raising and Seedling Management

A healthy nursery is the foundation of successful SMI cultivation. Seedlings are raised in well-drained, organic matter-rich nursery beds or micro-pots using a seed rate of only 200-250 g ha^{-1} compared to 5-6 kg ha^{-1} required in conventional sowing. Seeds are thinly sown at 8-10 g m^{-2}, and seedlings become ready for transplanting within 15-20 days. Seed treatment with a 10% garlic extract solution is recommended to protect against damping-off disease and improve seedling vigor (Satpathy, 2015).

Optimum Seedling Age and Transplanting

Transplanting young seedlings is a key feature of SMI. Research indicates that seedlings aged 15-25 days establish quickly, develop stronger root systems, and exhibit higher growth rates than older seedlings.

Seedlings are carefully uprooted and transplanted individually on ridges, ensuring minimal root damage. This practice helps achieve uniform plant populations and allows the crop to escape yield losses associated with delayed sowing after kharif crop harvest (Sushma *et al*., 2023).

Wider Spacing and Crop Management

SMI promotes wider spacing (45 × 30 cm to 60 × 60 cm) compared with conventional dense planting. Wider spacing reduces competition among plants for sunlight, nutrients, moisture, and space, leading to vigorous root growth, profuse branching, and increased siliqua production. Studies have shown that wider-spaced plants can produce substantially higher seed yields per plant due to better utilization of available resources. The line planting system also facilitates intercultural operations and mechanical weeding.

Nutrient, Water, and Weed Management

SMI advocates integrated nutrient management through the application of 2-3 t ha^{-1} farmyard manure (FYM), balanced fertilization, and adequate sulphur and boron supplementation, as mustard is highly responsive to these nutrients. Recommended doses include 75-120 kg N ha^{-1}, 35-40 kg P ha^{-1}, 20-40 kg K ha^{-1}, and 6 kg borax ha^{-1}. Irrigation is provided at critical growth stages, namely pre-flowering, full bloom, and pod formation, to maximize yield. Mechanical weeding using wheel hoes is encouraged not only for weed control but also for improving soil aeration and root activity. Botanical formulations such as garlic extract can be used as eco-friendly alternatives for pest management, particularly against aphids.

Benefits of SMI

The SMI has emerged as an innovative approach for enhancing mustard productivity through efficient crop and resource management.

By emphasizing healthy seedlings, wider spacing, transplanting, and improved crop husbandry, SMI creates favorable conditions for better plant growth and development. Studies have shown that SMI improves root proliferation, branching, dry matter accumulation, siliqua formation, and seed yield compared to conventional cultivation practices. Transplanting 25-day-old seedlings at wider spacing (60 × 60 cm) produced up to 656 siliquae plant^{-1} and significantly higher branching, demonstrating the superiority of SMI in maximizing the productivity of individual plants (Sushma *et al*., 2023).

Another major advantage of SMI is its higher resource-use efficiency. Wider spacing reduces competition among plants for sunlight, nutrients, moisture, and space, while transplanting ensures optimum plant population and better crop establishment. The integration of organic manures, balanced fertilization, timely irrigation, and mechanical weeding further enhances nutrient-use and water-use efficiency. These practices are particularly beneficial in rainfed and resource-constrained environments where efficient utilization of available resources is critical.

SMI also improves farm profitability and sustainability. Mahto *et al*. (2024) reported that Indian mustard grown under SMI recorded seed yields exceeding 2.0 t ha^{-1} with higher net returns and benefit-cost ratios than conventional cultivation. Reduced seed requirement, better input utilization, and higher yields contribute to increased profitability. At the same time, SMI promotes sustainable production by improving soil health, reducing environmental stress, and enhancing resilience to climatic variability.

Comparison of Conventional Sowing, Line Sowing and Transplanting in Mustard

Transplanting under SMI allows each plant to exploit available resources more effectively than conventional broadcasting or line sowing. Wider spacing encourages vigorous root growth and branching, resulting in higher yield per plant and ultimately greater productivity per unit area.

Aspect	Broadcasting	Line Sowing	SMI Transplanting
Method of establishment	Seeds are scattered randomly over the field.	Seeds are sown in rows at a fixed row spacing.	Nursery-raised seedlings are transplanted at wider spacing.
Seed requirement	Highest (4–6 kg ha^{-1}) due to uneven distribution and wastage.	Moderate (3–5 kg ha^{-1}).	Lowest (200–500 g ha^{-1}), saving 80–90% seed.
Plant population	Uneven and often overcrowded.	More uniform than broadcasting	Precisely maintained with optimum plant stand.
Root development	Restricted because of intense competition.	Better than broadcasting	Deep and vigorous root system due to wider spacing.
Light interception	Poor because plants shade each other.	Improve	Maximum light penetration to all plants.

Nutrient and water utilization	Less efficient due to overcrowding.	Moderate efficiency.	Highly efficient resource utilization.
Weed management	Difficult as rows are absent.	Easier due to row arrangement.	Most effective; intercultural operations are easy.
Branching and siliqua formation	Lower	Moderate	Highest due to reduced competition and better aeration.
Labour requirement	Lowest	Moderate	Highest initially due to nursery raising and transplanting.
Yield potential	Lowest	Moderate	Highest. Studies reported yields up to 3–5.7 t ha^{-1} under SMI.
Profit	Lower due to reduced productivity.	Moderate	Highest due to greater yield and resource-use efficiency.
Suitability for tribal and hilly areas	Less suitable because of poor resource-use efficiency.	Suitable where labour and management are available.	Highly suitable for small and marginal farmers aiming for higher productivity from limited land.

Resource-Use Efficiency Highlights under SMI

- Seed requirement reduced by 80-90% (200-500 g ha^{-1} *vs*. 4–6 kg ha^{-1} in conventional sowing.
- Dry matter production increased to 4.66 t ha^{-1} with 25-day-old seedlings under SMI (Sushma *et al*., 2023).
- 656 siliquae $plant^{-1}$ recorded at 60 × 60 cm spacing, indicating greater nutrient partitioning to reproductive structures.
- Farmers adopting SMI achieved 2-4 times higher yields than conventional cultivation in Madhya Pradesh and Bihar (Satpathy, 2015).
- Net returns up to ₹51,564 ha^{-1} and B:C ratio of 1.93 were reported under SMI-based mustard cultivation (Mahto *et al*., 2024).

Case Study 1: Productivity and Profitability of Brassica Species under System of Mustard Intensification (SMI)

A field study evaluated the performance of three Brassica species under different planting geometries using SMI principles. The results revealed that wider spacing and transplanting significantly improved growth, yield attributes, and profitability. Among the species tested, Indian mustard (*Brassica juncea* cv. Giriraj) produced the highest seed yield of 1967-2007 kg ha^{-1}, followed by Ethiopian mustard (*Brassica carinata*) with 1649-1682 kg ha^{-1}, while canola (*Brassica napus*) recorded the lowest yield of 1247-1272 kg ha^{-1}.

The highest net return (₹49,565-51,564 ha^{-1}) and benefit-cost ratio (1.90-1.93) were also obtained from *B. juncea*. Wider transplant spacing (60 cm × 60 cm) resulted in more primary and secondary branches, higher siliquae per plant, and better seed weight than conventional sowing. The study concluded that SMI improves individual plant performance by reducing competition and enhancing root growth, thereby increasing yield and profitability (Mahto *et al*., 2024).

Case Study 2: Effect of Seedling Age and Plant Geometry under SMI

A field experiment conducted at Agricultural College, Polasa, Telangana assessed different seedling ages and plant geometries under SMI. The study found that transplanting 25-day-old seedlings at 30 × 30 cm spacing recorded the highest plant height (193.2 cm) and dry matter production (4660 kg ha^{-1}). However, transplanting 25-day-old seedlings at 60 × 60 cm spacing produced the highest number of primary branches (9.0 $plant^{-1}$), secondary branches (24.6 $plant^{-1}$), and siliquae (656.3 $plant^{-1}$). These improvements were attributed to enhanced root development, reduced inter-plant competition, and better utilization of sunlight, moisture, and nutrients. Compared with conventional sowing, SMI significantly improved growth and yield attributes, demonstrating its potential for increasing mustard productivity under diverse agroecological conditions (Sushma *et al*., 2023).

Case Study 3: Effect of Broadcasting, Line Sowing and SMI on Mustard Growth and Yield

A two-year field experiment conducted at the Regional Research Station (Old Alluvial Zone), Uttar Banga Krishi Viswavidyalaya, West Bengal, evaluated three mustard establishment methods-broadcasting, line sowing, and System of Mustard Intensification (SMI)-using hybrid mustard varieties. The study revealed that SMI consistently outperformed both broadcasting and line sowing in terms of growth and yield parameters. The treatment involving Kesari Gold under SMI (V_3S_3) recorded the highest seed yield (1,875.26 kg ha^{-1}), dry matter accumulation (115.0 g $plant^{-1}$), leaf area index (4.46), and crop growth rate (6.43 g m^{-2} day^{-1}). Production efficiency was also highest under SMI, reaching 18.16 kg ha^{-1} day^{-1} in 2022 and 19.76 kg ha^{-1} day^{-1} in 2023. The superior performance of SMI was attributed to better crop establishment, enhanced root growth, optimum plant population, and efficient utilization of sunlight, moisture, and nutrients. The findings clearly demonstrated that transplanting-based SMI is more productive and sustainable than conventional broadcasting and line sowing methods (Pandit *et al*., 2025).

Scope of SMI in Tribal Hilly Agro-Ecosystems

Tribal and hilly agro-ecosystems are characterized by small and fragmented landholdings, rainfed farming, fragile soils, and limited access to agricultural inputs. Under such conditions, SMI offers tremendous opportunities for improving productivity and livelihood security. The technology requires less seed, optimizes resource use, and enhances crop performance even under low-input conditions. Improved root systems and wider spacing help crops better withstand moisture stress, making SMI suitable for climate-vulnerable regions.

Despite its advantages, adoption of SMI faces challenges such as limited awareness, additional labour requirements for nursery raising and transplanting, and inadequate extension support. However, increasing farmer training, demonstration programmes, farmer producer organizations (FPOs), and government support can accelerate its adoption.

With proper capacity building and institutional support, SMI can become a key technology for sustainable mustard production in tribal and hilly regions.

Conclusion

The SMI represents a sustainable and climate-resilient approach to mustard cultivation. By combining healthy seedlings, wider spacing, transplanting, and efficient resource management, SMI significantly improves growth, yield, profitability, and resource-use efficiency compared with conventional cultivation methods. Evidence from research trials and farmers' fields clearly demonstrates its potential to enhance mustard productivity while reducing pressure on natural resources. For tribal and hilly agro-ecosystems, where resource conservation and livelihood enhancement are equally important, SMI offers a promising pathway toward sustainable oilseed production, improved farm income, and long-term agricultural resilience.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine

Volume 04, Special Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-06

CLIMATE-RESILIENT OILSEED PRODUCTION SYSTEMS: GENETIC IMPROVEMENT AND NATURAL RESOURCE MANAGEMENT IN TRIBAL HILLY AGRO-ECOSYSTEMS

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Introduction

India has the world's fourth-largest vegetable oil economy, with oilseed crops contributing significantly to the agricultural economy, next only to cereals among field crops. The country's climatic diversity favours cultivation of nine oilseed crops: groundnut, rapeseed-mustard, soybean, sunflower, safflower, sesame, niger, linseed, and castor. However, low and unstable yields of most oilseed crops result from majority cultivation under rainfed conditions in poor soils with low organic carbon, creating high climate risk production environments.

Tribal hilly agro-ecosystems face particular challenges, including hilly terrain, lack of irrigation facilities, inferior quality seeds, rainfed cultivation, and traditional farming systems. Approximately 70% of soils in regions like Odisha are acidic, and oilseeds are grown without liming; oilseed crops are predominantly grown under rainfed/residual soil moisture conditions on marginal lands with low fertility. Niger and mustard are specifically grown by resource-poor tribal farmers who rarely adopt modern agricultural techniques.

Turning Climate-Smart Agronomic Practices into Productivity Gains:

Climate-smart agronomic practices (CSAPs) integrate adaptation and mitigation strategies to enhance productivity while reducing climate risks.

In tribal hilly regions, these practices include:

- **Conservation Tillage and Mulching**: Zero tillage or minimum tillage reduces soil erosion while maintaining soil organic carbon. Mulching with organic materials enhances in-situ soil moisture conservation by 20.6% under high rainfall conditions on moderate to steep slopes.
- **Rain Water Harvesting (RWH)**: Rain Water Harvesting systems with PRS (Percolation Pond System) of 65 have been successfully implemented in Ayeng village, East-Siang District, Arunachal Pradesh, demonstrating effective water management in hilly agro-ecosystems.
- **Intercropping Systems**: Intercropping offers solutions for higher yield per unit area and reduced risk of crop failure under unpredictable rainfed conditions. The soybean + pigeon pea (4:2) system gave benefits of 40-60% in different sites of Kurnool (Andhra Pradesh), Aurangabad, and Nandurbar districts (Maharashtra).

Location-specific cropping systems matter as much as individual practices. In rainfed and residual-moisture environments, oilseeds can be introduced into rice fallows, upland systems, and intercropping models to improve land-use

efficiency and income stability. For tribal hilly regions, combinations such as oilseed-based intercropping, relay systems, and cover-crop-based rotations can spread risk and improve overall productivity.

Accelerating Climate-Ready Oilseed Improvement with Genetics and Biotechnology:

Climate resilience in oilseeds depends heavily on breeding for drought, heat, and other stress tolerance, along with higher yield and quality. Conventional breeding remains essential, but modern programs increasingly use molecular breeding, genomics, and genome editing to accelerate the development of stable cultivars. Heat stress is especially damaging during reproductive stages, so traits such as pollen viability, membrane stability, antioxidant defence, and reproductive success are key breeding targets.

Key approaches include:

- **Conventional Breeding Methods**: Mass selection, pure-line selection, and backcross breeding remain powerful tools alongside molecular approaches. These methods accelerate development of high-yielding and stress-tolerant varieties.
- **Utilization of Indigenous Germplasm**: Valuable donors for various biotic and abiotic stresses, with variability in agromorphological and quality characters, have been identified among indigenous Indian mustard germplasm.
- **Augmented Germplasm Accessions**: Out of 1,30,984 augmented indigenous germplasm accessions of seven crops, 30% stress-tolerant accessions were used in breeding during 2005-2009, demonstrating the critical role of indigenous genetic resources.

Biotechnology can strengthen oilseed improvement by identifying stress-response genes, improving selection efficiency, and enabling precise trait modification. Recent work highlights heat shock factors, calcium signalling pathways, MAP kinase cascades, and ABA-related regulators as important components of stress adaptation in oilseeds. Tools such as *omics-assisted breeding*, *marker-assisted selection*, and *CRISPR/Cas-based editing* can help combine stress tolerance with high yield and quality. Figure.1. illustrates the different oilseed crops that are CRISPR-edited for their oil quality improvement. Although, these modified oilseed crops are not being currently by the tribal people but it has immense potential to be used efficiently in the coming future.

Empowering Farmers through Participatory Variety Selection and Location-Based Production System

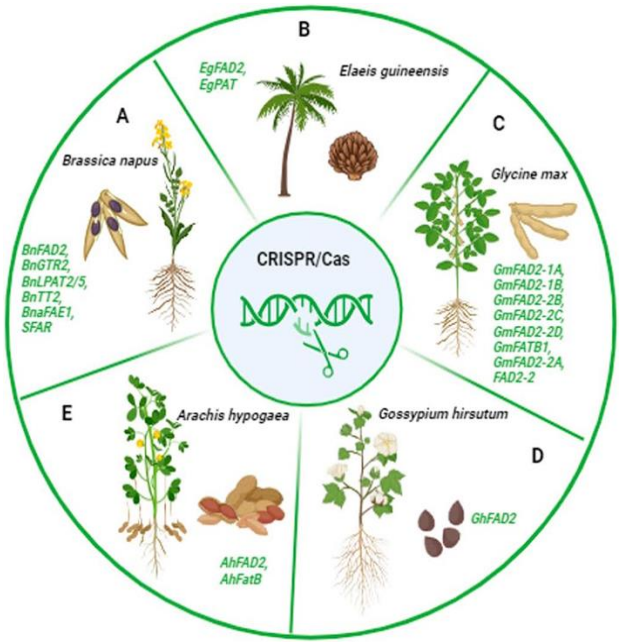


Figure 1. Schematic representation of the different CRISPR-edited oilseed crop

Participatory varietal selection (PVS) strengthens the link between breeders and farmers by identifying varieties that fit local soil,

climate, cooking quality, and management preferences. This approach is especially useful in tribal areas because farmers often manage highly variable micro-environments and possess deep knowledge of local performance differences. It also improves adoption because farmers help choose varieties before large-scale dissemination.

PVS (Participatory Varietal Selection) Methods:

- **Mother Trials:** Small-scale trials conducted across representative districts
- **Baby Trials**: Larger validation trials (500m^2) conducted across villages
- **Farmer Walks**: Organised prior to harvest, allowing farmers to evaluate varieties
- **Secret Ballot Selection**: Farmers rank and select varieties independently

Farmer Selection Criteria: Farmers consider hydrological conditions (water depth), land types (toposequence), variety adaptation to user needs (food, fodder, cash), compatibility in cropping systems, and socioeconomic factors including gender and culture.

Location-Based Production Systems:

- **Eastern Plateau and Hills Region**: This is the largest agro-climatic zone covering about 400,000 sq.km with average annual rainfall suitable for rice, oilseeds, groundnut, soybean, and castor.
- **North Eastern Hill Region**: Characterized by high soil acidity/aluminium toxicity, heavy soil, carbon loss, and severe water scarcity despite high rainfall. Shifting cultivation has erosion ratio of 12.46 and soil loss of 30.2-170.2 t/ha/yr. Agroforestry systems (Agri-Horti-Silvi-pastoral) performed better than shifting cultivation, improving soil organic carbon by 44.8% and reducing soil loss by 99.3%.
- **Tribal Sub-Plan Programme**: Implemented in 48 villages across 10 districts spanning seven states (Andhra Pradesh, Rajasthan, Karnataka, Tamil Nadu, Telangana, West Bengal, Chhattisgarh) to reduce poverty among scheduled tribe populations and create productive assets.

Transforming Oilseed Farming Through Innovative, Community-Driven Solution:

- **Rice Fallow Intensification**: A multi-state initiative under National Food Security Mission (NFSM)-Oilseeds promoted sunflower cultivation in 8,000 hectares of rice fallows across six states (Bihar, Chhattisgarh, Jharkhand, Karnataka, Odisha, West Bengal) during 2024-25 rabi season. Sunflower's low water requirement and adaptability to residual soil moisture make it climate-resilient.
- **Beekeeping Integration**: 150 beekeeping demonstration units (110 in Karnataka, 40 in Odisha) enhanced sunflower yields through improved pollination and offered additional income from honey production. This catalysed local interest in beekeeping, especially among women's groups in tribal districts.
- **Women's Participation**: 44.8% of participating farmers were women, emphasizing strong gender inclusivity. Women's participation was particularly high in Jharkhand (98.7%), Odisha (60.8%), and Chhattisgarh (60.1%), achieved through targeted mobilization via SHGs and training programs.

- **Marginalized Group Outreach**: Scheduled Tribes comprised 36.6% and Other Backward Castes 41.2% of participants. Jharkhand and Chhattisgarh had highest ST representation at 76.1% and 83.7%, respectively. Tailored engagement strategies ensured inclusion of communities traditionally excluded from high-value crop cultivation.

Case Study 1: **NICRA Villages, Ganjam District, Odisha**

National Innovation on Climate Resilient Agriculture (NICRA) villages in Ganjam district demonstrated drought-tolerant groundnut variety Devi (ICGV 91114) *with* successful cultivation of onion and sunflower during rabi season. Because Devi matures early (90–95 days) and tolerates drought, farmers could harvest on time and successfully grow rabi crops such as onion and sunflower, this location-specific production system enhanced resilience to climate variability.

Yield improvement reached approximately 40% over the local variety under drought stress conditions. The drought-tolerant groundnut variety Devi (ICGV 91114) in a NICRA village in Ganjam district, Odisha, along with the farmers, as shown in Figure 2.



Figure 2. Drought- tolerant groundnut variety Devi (ICGV 91114) in Ganjam under NICRA

Restoring Soil, Feeding Crops, and Securing Water for Climate-Ready Oilseed Systems:

1. Soil Health Restoration

- Soil Organic Carbon Enhancement: Agroforestry systems improved soil organic carbon by 44.8% under high rainfall, moderate to steep slopes, and shallow soil depth conditions. Multipurpose trees (MPTs) played important roles in soil rejuvenation.
- Resource Conservation Techniques: Zero tillage/minimum tillage, hedge crop, mulching, and cover crop need attention for building organic matter status and sustaining soil health in degraded resource conditions.

2. Nutrient Management for Sustained Productivity

- Integrated Nutrient Management (INM)**:** INM is key in hilly regions where nutrient transfer causes environmental degradation. In northeastern India, excessive deforestation and shifting cultivation resulted in tremendous soil loss (200 t/ha/yr) and nutrient transfer estimated at 601 million tons of soil and 685.8 thousand tons of N.
- Balance Nutrient Application**:** Balancing the application of plant nutrients and maintaining their concentration in soil solution through organic and inorganic substances is essential for enhancing oilseed production in hilly areas.

3. Water Management that keeps the crop alive

- In-situ Moisture Conservation**:** Agroforestry systems achieved 20.6% in-situ soil moisture conservation under high rainfall and steep slope conditions.

- Irrigation Management**:** Management of irrigation and tillage operations is key to enhancing oilseed production in hilly areas with poor water retention capacity.

Conclusion:

Climate-resilient oilseed production in tribal hilly agro-ecosystems requires integrated implementation of climate-smart agronomic practices, genetic improvement using indigenous germplasm and biotechnological tools, and participatory varietal selection for location-specific adaptation. Case study from Odisha tribal hills demonstrate that farmer participation, conservation agriculture integration, and indigenous technology utilization significantly enhance productivity and resilience. However, implementation challenges, infrastructure constraints, resource poverty, climate variability, knowledge gaps, and market access limitations hinder widespread adoption. Future directions must prioritize genetic enhancement through advanced breeding, digital tool integration, policy support for tribal farmers, integrated research on conservation systems, extension strengthening, and community seed system development. Only through such multi-dimensional approaches can India achieve edible oil self-reliance while ensuring livelihood security for tribal communities in vulnerable hilly ecosystems.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine
Volume 04, Special Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-07

SOIL MOISTURE CONSERVATION APPROACHES FOR OILSEED CROPS IN HILLY AND TRIBAL REGIONS

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Introduction

Hilly and tribal areas are rich in natural resources, but farming in these regions is often difficult because of uneven rainfall, soil erosion, and lack of irrigation facilities. Oilseed crops, which are important for food and income, require adequate soil moisture for better growth and yield. Soil moisture conservation methods such as mulching, contour farming, terracing, and rainwater harvesting help in retaining water and protecting the soil. These techniques not only improve crop productivity but also support sustainable agriculture and the livelihoods of tribal farmers. Therefore, adopting suitable soil moisture conservation approaches is essential for increasing oilseed production and ensuring agricultural development in these areas.

1. Why Soil Moisture Matters So Much?

The biggest problem in hilly areas is that the weather is completely unpredictable. If monsoon stops early in the season, the top layer of the soil dries out fast. This is problematic for crops like linseed because the plants are naturally short and have shallow root system i.e. it draws water from the top layer of soil. If such condition appears at the time of onset of flowering then the crop suffers from massive moisture stress.

- **High evaporation:** The young plants grow slowly at first, they don't create enough leaf canopy to shade the ground. The bare dirt is left completely exposed to the sun, causing water to evaporate rapidly.
- **Topsoil depletion:** This exposure causes a massive 46.2% soil moisture loss in the topmost layer (0-15 cm depth).
- **Nutrient blockade:** when there is no water in the upper soil, the plant cannot absorb vital nutrients, which completely stunts its growth and tanks the final yield.

2. Key Soil Moisture Conservation Approaches

a. Traditional Tribal and Indigenous Approaches

i. Low-cost water harvesting structures (Jalkund)

- **Structure:** Tribal farmers construct low-cost structures (jalkund) with a storage capacity of 30-90m^3 before the onset of monsoon. The jalkund stores between 30,000 to 94,000 litres of sediment-free rainwater harvested from upper catchments.
- **Benefit:** It has a shelf life of 3 years. The 90m^3 jalkund can provide off-season irrigation for winter produce, accumulate livestock and fish farming water requirements and diversify income stream for smallholders.

ii. Stone and stone-cum vegetative bunding: It is constructed manually using locally collected stones typically 15-20 cm in size stone bunds are built along field boundaries or across slopes.

- To optimize these farmers plant reinforcing shrubs along the stone structures.
- On an 11% slope, stone bunds have proved to reduce 54% runoff and soil loss by 60%.
- It created a stabilized, moisture-rich micro-topography ideal for oilseeds.
- Stone-cum-vegetative bunding have significantly increased 20% more yield than normal.

iii. Jhola Kundi (Circular micro water harvesting): In low-lying creek areas (jhola lands) farmers manually dig circular ponds measuring 2 to 4 meters deep.

- By depositing the excavated earth as a protective boundary around the perimeter, they prevent surface siltation. The stored water provides vital life line for nearby oilseeds during dry spells.



Jhola Kundi

B. In-situ Soil Moisture Conservation Approaches

i. Mulching: A soil mulch is created by hoeing the field 30 DAS using a narrow iron spade. An additional hoeing can be performed immediately following the first light winter rain shower. This method boosts seed yield roughly 32.5% (877 to 879 kg/ha) over non-treated plots.

- **Bio-mulching:** Application of succulent weed biomass or crop residues minimizes evaporation losses, enhances water infiltration and improves soil structural pore geometry during decomposition. Dual application of succulent weed biomass @ 5.0 tonnes/ha have been shown to double crop yields and boost water productivity by up to 95% under moisture-stressed condition.
- **Straw mulching**: Soybean straw mulch can be spread at the rate of 10 t/ha uniformly over the soil surface at around 30 DAS. This approach delivers highest agronomic dividends. It increases seed yield by up to 564% (1037 kg/ha) and oil yield by 525% (403.3 kg/ha). It reduces topsoil moisture depletion.
- **In-situ weed mulching:** This method is useful for low-input tribal agriculture. Common field weeds like *Chenopodium album, Chenopodium murale, Convolvulus arvensis and Cynodon dactylon* are uprooted at 30 DAS and their fresh biomass are placed directly in between crop rows. This handles weed competition while simultaneously creating a protective cover to reduce evaporation. It leads to increase in seed yield by 29.6%.



In-situ weed mulching

ii. Contour bunding: It is constructed across slopes of 2–6% in low-rainfall areas (below 600 mm). It helps capture runoff and enhance soil moisture. In semi-arid and tribal regions, bunding interventions have increased crop yields by over 14% and an improvement in WUE by about 10%. Field evidence from Rajasthan shows that implementing contour bunds for mustard cultivation increases economic and biological yields by 14.4% and 15.3%, respectively, compared to fields with no bunding.



Contour bunding

iii. Broad Bed Furrow (BBF): This configuration is highly beneficial for controlling topsoil loss while providing necessary drainage during heavy tribal area monsoons.

- It features a raised flatbed about 95 cm wide accompanied by shallow furrows roughly 55 cm wide and 15 cm deep laid across the field slope.
- BBF effectively manages extreme weather by draining excess water during heavy downpours and retaining moisture during dry spells.
- Cultivating oilseeds like soybean on BBF has been shown to boost crop yields by 21% alongside giving superior net returns compared to traditional flatbed planting.



Broad Bed Furrow

iv. Ridges and Furrows: It is opened across the main land slope ideally fields with a 1–3% slope and a furrow gradient of 0.2–0.4%. This system is highly effective for in situ rainwater conservation. In vertisols, the ridge-and-furrow method significantly improves crop performance, increasing water use efficiency (WUE) and overall productivity.

C. Vegetative Barriers: It is also referred to as live bunds. These consist of closely spaced rows of sturdy grasses (such as Vetiver, Guinea, or lemon grass) planted along contours. They serve as low-cost alternatives to physical structures, slowing down runoff, trapping sediment, and expanding soil moisture. For groundnut systems, vegetative barriers implemented alongside contour trenching have been documented to cut runoff by 20% and soil loss by 51%.

D. Geotextiles: In high-rainfall hilly areas and non-arable lands, bio-engineering solutions using geotextiles provide unparalleled stability. These are woven mats made out of natural fibers like jute, coir, or giant cane that protect slopes and riverbanks while increasing moisture retention. Deploying geotextiles within rainfed groundnut cultivation systems dramatically improves land productivity—boosting crop yields by 36% to 64% and enhancing soil organic carbon (SOC) by up to 53%.



Geotextiles

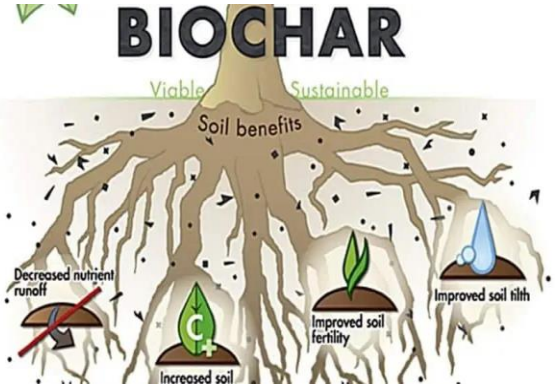
E. Bench Terracing and Trenching: For steep hilly terrains with slopes between 16% and 50%, bench terracing transforms steep land into steps of level strips supported by risers, greatly reducing soil and moisture losses. Similarly, contour trenching (digging small trenches on slopes up to 20%) captures running water to actively recharge soil moisture in adjacent cropping zones, which proves highly effective in semi-arid regions with shallow soils.



Bench terracing

F. Biochar Application

- Instead of burning forest and weed phytomass in open aerobic environments, resource-poor farmers can convert this biomass into biochar via anaerobic pyrolysis inside closed trenches.
- Biochar elevates the carbon content from 40% (in fresh biomass) to 70–80%, expanding the decay half-life to over 80 years.
- This serves as a reliable carbon sink while vastly increasing the soil's surface absorption area and long-term moisture retention capacity.



Conclusion

Adopting structured soil moisture conservation practices is essential to overcome farming challenges in hilly and tribal regions. Traditional indigenous techniques, such as constructing Jalkund structures and stone bunds, drastically minimize topsoil erosion and runoff while optimizing water accumulation.

Concurrently, modern in-situ approaches including organic straw mulching, contour bunding, broad bed furrows, geotextiles, and biochar application effectively suppress high evaporation rates and enrich soil organic carbon.

Ultimately, integrating these diverse soil moisture interventions drastically maximizes oilseed yield parameters and water use efficiency, securing agricultural development and stabilizing tribal livelihoods against unpredictable monsoonal climates.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine

Volume 04, Special Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-08

ASSESSMENT OF DIVERSIFIED OILSEED-BASED CROPPING SYSTEMS FOR ENHANCING PRODUCTIVITY, RESOURCES USE EFFICIENCY AND SUSTAINABILITY

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Introduction

Oilseed crops are generally one of the most important crops in the world. Their role in human diet and industrial application cannot be under estimated. The by-products like hull, meal and oil of oilseed crops had been integrated into human and animal diets due to their nutrient compositions. Oilseed meals consist of protein, high fat yields, high contents of essential amino acids, vitamins A, D, E and K and trace elements, which are beneficial to human health and well-being. Several industrial products such as bio-diesel, fertilizer, medicine, animal feeds, fibers, etc. have also been reported.

India is one of the world's largest producers of oilseeds. Major oilseed-growing states include Rajasthan, Madhya Pradesh, Gujarat, Maharashtra and Karnataka. India's oilseed and oil meal exports generated approximately Rs.9340 crores (approx. US$ 1.1 billion) in foreign exchange for the 2025-26 marketing year. The revenue saw a decline of approximately 23% as compared to previous years, driven by Red Sea shipping disruptions, higher freight costs and intense global competition. To boost overall agricultural resilience and production capacity, the government allocated a substantial sum of Rs.1.30 lakh crores for agricultural development under the 'Department of Agriculture and Farmers Welfare' to further improve oilseed yields.

Some major challenges faced by oilseed production are as follows:

- The yield of many oilseed crops is lower than that of similar crops in other countries, resulting in low productivity.
- Farmers often do not have access to high-quality seeds and improved varieties.
- Oilseed crops are affected by various pests and diseases, which reduce yield and quality.
- Insufficient irrigation facilities restrict crop growth and productivity.
- Farmers face uncertainty due to frequent fluctuations in market prices.
- Inadequate storage, processing and transportation facilities lead to post-harvest losses

Diversification in oilseed-based farming systems is essential for improving farm income and reducing the risks associated with crop failure. It helps in the efficient use of land, water, labor and other resources throughout the year; improves soil fertility, enhances biodiversity and promotes sustainable agriculture. By integrating crops, livestock, horticulture or agroforestry with oilseed cultivation, farmers can achieve better profitability, nutritional security and resilience to climate change.

Understanding Cropping System Diversification

Concept and Significance

Crop diversification has been recognized as an effective strategy for achieving the objectives of food security, nutritional security, income growth, employment generation and sustainable agricultural development. The necessity for crop diversification arises on account of the need for reducing risks associated with yield, market and prices; arresting the degradation of natural resources and the environment and attaining national goals like employment generation, self-reliance in critical crop products and for earning foreign exchange. The crop diversification also takes place due to government policies and thrust in some crops over a given time. For example, creation of Technology Mission on Oilseeds (TMO) to give thrust on oilseed production as a national need for country's requirement to reduce imports.

India's diverse agro-ecological conditions enable the cultivation of 9 annual oilseed crops, including groundnut, rapeseed-mustard, soybean, sunflower, sesame, safflower, niger, castor and linseed. However, a major challenge lies in rainfed agriculture, with 76% of the oilseed cultivation area contributing 80% of total production. India's total oilseed production for the 2025-26 crop year is estimated at 40.99 million tons, according to the Ministry of Agriculture's Second Advance Estimates. This marks a decrease of approximately 3.7% compared to the record production of 42.60 million tons achieved in the previous year. Currently, India is the world's top Importer and second largest consumer of edible oils in the world. Achieving self-sufficiency in edible oils through increasing area and productivity of oilseed crops and crop diversification with oilseeds is the need of the hour.

Types of Cropping Systems for Oilseed Crops

Cropping systems for oilseed crops (like soybean, groundnut, and mustard) are designed to optimize soil health, manage pests, and maximize land productivity. The most common methods include:

Sole Cropping (Monocropping): Sole cropping is the cultivation of a single crop species in a field during a growing season. It allows easy management and efficient use of inputs.

Examples: Groundnut (See Fig.1.), Soybean, Sunflower, Sesame.



Fig. 1. Sole cropping of Groundnut

Intercropping: Intercropping involves growing two or more crops simultaneously on the same field in a definite row arrangement. It helps in better utilization of resources and reduces the risk of crop failure.

Examples: Sorghum+ Pigeon pea (See Fig. 2.), Soybean+ Maize, Sesame+ Black gram, Sunflower+ Green gram.



Fig. 2. Intercropping of Sorghum+ Pigeon pea

Sequential Cropping: Sequential cropping is the practice of growing two or more crops one after another on the same land within a year. The succeeding crop is planted after harvesting the previous crop.

Examples: Groundnut→ Safflower, Sesame→ Wheat (See Fig. 3.), Soybean→ Chickpea.



Fig. 3. Sequential Cropping of Sesame Crop

Relay Cropping: Relay cropping is a system in which the succeeding crop is sown before the harvest of the standing crop, allowing both crops to share part of their growth period.

Examples: Sowing lentil (See Fig. 4.) or lathyrus in standing rice before its harvest, sowing safflower in standing sorghum.



Fig. 4. Relay Cropping of Lentil in Rice Fields

Paira/Utera Cropping: Paira or Utera cropping is traditional form of relay cropping practiced mainly in Central India. Seeds of the next crop are broadcasted into the standing crop without any tillage, utilizing the residual soil moisture after harvest.

Examples: Lathyrus, linseed (See Fig. 5), mustard or safflower Broadcast in standing rice field before rice harvest.



Fig. 5. Paira/Utera Cropping of Linseed in Rice Fields

Advantages of Diversified Cropping Systems over Monocropping

Diversified cropping systems outperform monocropping by enhancing soil fertility, boosting pest resistance, and increasing yield stability.

Growing different crops together or in sequence utilizes land, water, nutrients and sunlight more efficiently, resulting in higher overall production.

Diversification minimizes losses caused by adverse weather, pests, diseases or market fluctuations, as all crops are unlikely to fail simultaneously.

Inclusion of legumes in the cropping system enhances soil nitrogen content and improves soil health.

Different crops use resources at different times and depths, leading to efficient utilization of soil moisture, nutrients and sunlight.

Diversification improves long-term productivity and environmental sustainability compared to continuous monocropping.

Major Diversified Oilseed-Based Cropping Systems

Groundnut-based Systems

Sequence Cropping: In general, groundnut crop is rotated with cereals, oilseeds and commercial crops, following groundnut is usually increased by 25%. Promising crop sequences for Andhra Pradesh are:

Rainfed (2 years)	Stored Soil Moisture (2 crops/year)	Irrigated (2-3 crops/ year)
Groundnut+ Sorghum	Groundnut+ Chickpea	Groundnut+ Maize
Groundnut+ Pearl Millet	Groundnut+ Safflower	Groundnut+ Onion
Groundnut+ Sesame	Groundnut+ Sesame	
Groundnut+ Tobacco		

Intercropping: Groundnut is intercropped with cereals like pearl millet, sorghum and maize. Other long duration intercrops like pigeon pea, cotton, castor and short duration intercrops like sesame, sunflower, cowpea, black gram, green gram are grown with groundnut.

Rapeseed and Mustard-based Systems

Mixed Cropping: Its is grown as a mixed crop with wheat, barley during winter season.

Intercropping: Brassicas are generally intercropped with rabi crops. Some profitable systems are:

a. Wheat+ Mustard (4:1)

b. Gram+ Mustard (4:2)

c. Barley+ Mustard (6:1)

Intercropping in autumn planted sugarcane (Adsali) has increased the net returns without affecting the yield of sugarcane.

Soybean-based Systems

Mixed Cropping: Mixed cropping of Soybean with Maize has been found feasible and more remunerative.

Intercropping:

a. Soybean+ Maize (2:1, 2:2)

b. Soybean+ Groundnut (1:4, 1:6)

c. Soybean+ Sorghum (1:2, 2:2)

d. Soybean+ Cotton (1:3, 2:1)

Sesame-based Systems

Crop Rotation: Crop rotation systems mainly followed in AP are:

a. Rice/Groundnut – Sesame

b. Sesame – Horse gram – Chickpea

c. Cotton – Sesame – Wheat

Intercropping:

a. Sesame + Green gram (1:1)

b. Sesame + Soybean (2:1)

c. Sesame + Cowpea (8:1)

Impact of diversified cropping systems on oilseed production and its contribution towards sustainability

Diversified cropping systems enhance resource-use efficiency, improve soil fertility, reduce pest and disease incidence and provide better moisture utilization. Major impacts include:

Legume-oilseed diversified systems increased overall production by about 33-112% compared with conventional wheat– oilseed and fallow– oilseed systems.

Intercropping systems involving mustard, groundnut, soybean, safflower and castor generally produce greater land-equivalent yield than sole cropping.

Diversified systems reduce yield fluctuations caused by drought, pests and market uncertainties.

Diversified oilseed farming systems generate higher net returns and benefit-cost ratios than monocropping due to efficient resource utilization and multiple outputs.

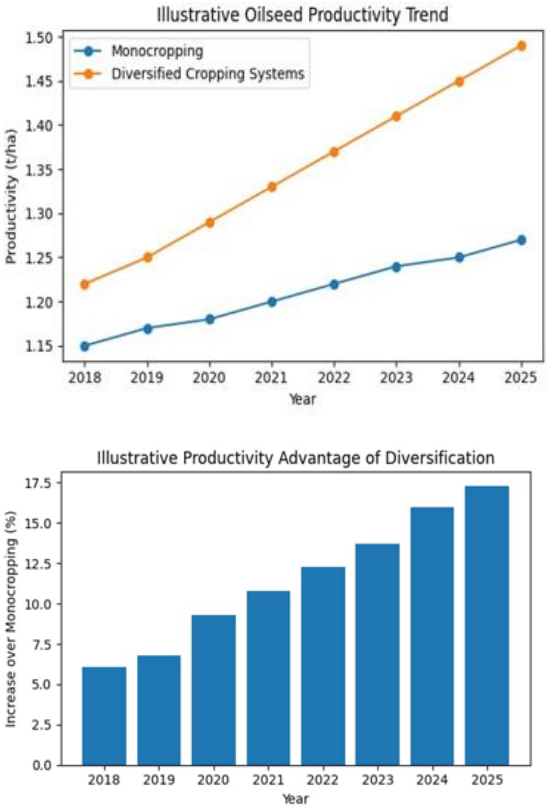


Fig. 6. Impact of Diversified Cropping Systems on Productivity of Oilseeds

Diversified cropping systems consistently recorded higher productivity than monocropping. Productivity under diversified systems increased from about 1.22 t/ha in 2018 to 1.49 t/ha in 2025, whereas monocropping increased from 1.15 t/ha to 1.27 t/ha during the same period (Fig. 6.). The widening gap between the two lines indicates that diversification provides greater benefits over time rather than monocropping.

The percentage increase in productivity obtained through diversified cropping systems compared to monocropping. The productivity had a gradual and consistent increase from approximately 6% in 2018 to 17% in 2025. This trend suggests that the benefits of diversification become more pronounced over time compared to monocropping.

Integrating oilseeds into crop rotations, intercropping, and agroforestry addresses agricultural sustainability (Fig. 7.) through several key mechanisms:

Deep-rooting oilseed crops (like safflower and castor) break up hard subsoil layers, improving aeration and water infiltration. Their taproots extract nutrients from deeper soil horizons, making them available to subsequent shallower-rooted crops.

When oilseeds (especially legumes like soybean or groundnut) are rotated with heavy-feeding cereals, they leave residual nitrogen in the soil, effectively reducing the reliance on synthetic fertilizers and lowering the carbon footprint.

Relying on a single staple crop (monoculture) exposes farmers to massive economic risks if weather or market prices crash. Oilseeds provide a secondary revenue stream and act as a hedge against total crop failure.

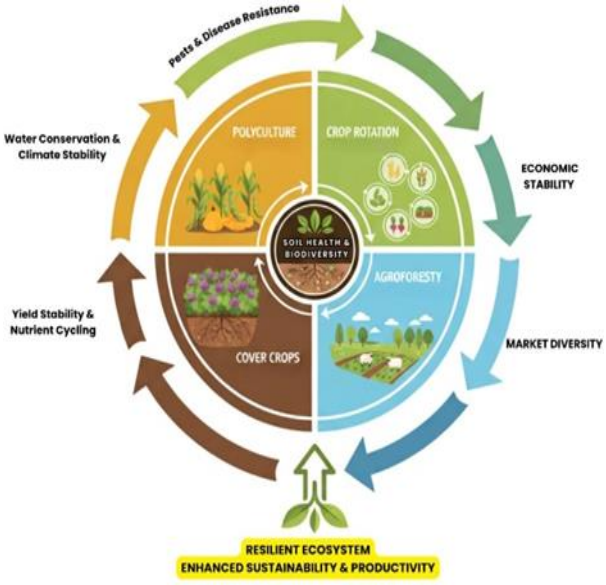


Fig. 7. Contribution of Diversified Cropping Systems towards Sustainability

Challenges of adapting diversified cropping systems for oilseed crops

- Oilseeds are highly susceptible to fluctuating global prices and lack guaranteed minimum support in many regions, making diverse rotations a final gamble.
- Diversifying requires investing in new seeds, specific fertilizers and localized crop protection protocols, which increase the financial burden on smallholder farmers.
- Oilseeds often require different sowing windows and specialized harvesting techniques compared to traditional crops, increasing operational stress.
- Agricultural extension services often focus heavily on monoculture cash crops (like cotton), leaving farmers with limited localized expertise for managing diversified oilseed systems.

Conclusion

Diversification of oilseed-based cropping systems is an effective strategy for improving productivity, profitability and sustainability in agriculture. By integrating oilseeds with cereals, pulses, fodders and other crops through relay cropping, intercropping, etc., farmers can enhance soil fertility, improve resource-use efficiency and increase cropping intensity. Although challenges such as limited access to quality inputs, inadequate market support and lack of technical knowledge may hinder adoption; appropriate research, extension services and policy support can promote wider implementation of diversified oilseed-based farming systems.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine
Volume 04, Special Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-09

DEVELOPMENT OF CLIMATE-RESILIENT OILSEED PRODUCTION SYSTEMS THROUGH NATURAL RESOURCE MANAGEMENT IN TRIBAL HILLY AGRO- ECOSYSTEMS

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Introduction

Tribal hilly agroecosystems face innumerable sufferings of climate change, which include erratic rainfall, temperature extremes, and land degradation, which severely impact oilseed productivity and its production. This article explores integrated strategies and frameworks for building climate resilience through crop genome improvement of oilseeds and sustainable natural resource management (NRM). The article highlights the role of the next generation of breeding tools- genomic selection, genome editing, speed breeding and utilization of indigenous germplasm for stress tolerance and yield enhancement. The techniques are highly plausible for the development of heat-tolerant cultivars of sesame, groundnut, rapeseed and niger crops.

Concurrently, NRM practices such as agroforestry, rainwater harvesting, drip irrigation and organic soil management discipline enhance water retention, reduce slope erosion and improve soil fertility. Case studies from Jawadhu hills of Tamil Nadu, Niyamgiri hills of Odisha and other tribal hilly regions demonstrate that integrating climate-smart seeds, resource-efficient practices with NRM interventions can potentially boost crop productivity by 30-50% and provide tribal livelihoods a stable source of income.

Oilseed crops are vital for global nutrition, providing fat, a healthy source of plant protein and essential sulphur-containing amino acids such as methionine and cysteine available for both human and livestock diets. Oilseeds also contribute to renewable energy sources and reducing carbon footprints. However, climate change poses unparalleled consequences: drought is the most challenging stressor, threatening food security, particularly in minor ecosystems like tribal hilly regions. In Indian tribal hills, marginal rainfed irrigation, eroded soils, and vulnerable farming systems augment these risks. Achieving climate resilience requires a two-way approach: genetic improvement for stress-tolerant varieties using biotechnology and sustainable natural resource management to optimize water, soil, and biodiversity.

2. Key Oilseeds contributing to tribal farming agro-ecosystems in India:

Sesame

Sesame is a classic low-input, climate-resilient crop that thrives where other crops fail. Under NRM practices like minimum tillage or mixed cropping, its incredibly deep root system allows it to scavenge for nutrients and moisture from lower soil layers, making it highly drought tolerant. Tribal farmers frequently utilise sesame in crop rotations to break pest cycles and conserve soil moisture.

Groundnut

Groundnut acts as an exceptional conservation crop in NRM due to its nitrogen-

fixing capabilities and dense, low-growing canopy. In tribal areas prone to erosion in sloped lands, groundnut forms a green blanket that significantly reduces soil erosion. As a legume, it fixes atmospheric nitrogen, enriching poor tribal soils and reducing the need for expensive fertilisers, and the deep taproot system improves soil structure.

Rapeseed

Typically grown in the *rabi* season following rice, rapeseed is vital for maximising land use efficiency and maintaining continuous soil cover. In the NRM framework, it serves as an excellent catch crop that utilises leftover residual soil moisture, preventing the land from lying fallow and degrading. Its rapid early growth suppresses weeds naturally, and its fibrous root system stabilises the topsoil against wind and water erosion during the dry winter months.

Sunflower

Sunflower introduces immense ruggedness and architectural diversity to tribal farming. Its deep, powerful root system acts as biological tillage, breaking up compacted soil layers and opening up channels of water infiltration. Furthermore, sunflowers are highly efficient at phytoremediation- absorbing and accumulating heavy metals or excess minerals from the soil- which helps maintain soil health.

Niger

Niger is perhaps the most culturally and ecologically integrated oilseed in tribal ecosystems, particularly on marginal, rocky and acidic hill slopes. It requires virtually zero chemical inputs and acts as a superb weed smotherer due to its aggressive early growth and allelopathic properties. In NRM, niger is frequently used as a boundary or cover crop because its unpalatable leaves naturally deter grazing cattle, protecting the entire farming plot while restoring organic matter to highly degraded lands.

Table 1. Summarises the list of Important oilseeds and their significance in tribal farming regions.

Crop	Importance	Resilient trait needed
Sesame	Minimum water needs, high tribal adoption	Drought tolerance
Groundnut	High protein and oil source, cash crop	Heat and dry weather tolerance
Rapeseed	Cold intolerance, grows well in hilly regions	High temperature tolerance
Sunflower/ Niger	Short duration, easily adaptable in various soil conditions	Drought resilience

Why is there a need for NRM intervention practices in the agro-ecosystems of hilly tribal regions?

Tribal hilly agro-ecosystems are highly vulnerable regions characterised by steep undulating terrains, fragile topsoils and severe dependency on rainfed agriculture. Indigenous tribal communities in these remote hills historically depend on low-input, monocropped subsistence agriculture, rendering them highly vulnerable to variable climate change realities like inconsistent precipitation, dry spells and warming temperatures. Oilseeds such as sesame, mustard, linseed, soybean, niger, sunflower, and

groundnut represent crucial functions that can withstand to climate adaptations and livelihood stability in such regions. However, traditional production systems face frequent threats from high surface runoffs, nutrient leaching losses and severe soil erosion. Developing a climate-resilient production system through Natural Resource Management (NRM) practices is essential to reverse environmental depletion, diversify tribal income, and ensure local food security.

The primary environmental bottleneck in tribal landscapes is rapid loss of water and soil nutrients, a crisis intensified by climate change. Inconsistent downpours trigger rapid topsoil erosion on slopy terrains, stripping the land of its essential organic matter and soil structure. Implementing NRM practices such as agroforestry, rainwater harvesting, drip irrigation, organic fertilizers, crop diversification, minimum tillage operations and contour trenching-minimises groundwater depletion and surface runoff while enhancing soil moisture content. These interventions capture rainwater, allowing oilseed crops to maximise residual soil moisture during the *rabi* season. Therefore, integrating integrated nutrient management (INM) and community-regulated organic waste composting helps restore soil health without relying much on expensive and intensive chemical fertilizers, lowering carbon credits in vulnerable agroecological zones.

Beyond resource conservation, building a resilient oilseed system directly focuses on nutritional insecurity and the economic exclusion of tribal indigenous communities. Incorporating oilseeds into multiple cropping systems with short-duration legumes and pulses promotes land use efficiency and welcomes climate-resilient diversification. For example, experimental evaluation of pulse-oilseed double-cropping models with rainwater stewardship significantly increased crop yields and macronutrient intake under rainfed conditions.

Oilseeds are rich in dietary fats, which are vital for resolving severe malnutrition among tribal societies. Generating a marketable surplus of oilseeds, which also empowers smallholders-particularly tribal women – to participate in local value addition supply chains and common interest groups, thereby transforming climate-sensitive subsistence farming into sustainable micro-enterprises.

Agroforestry: Agroforestry integrates woody perennials with crops on the same land management unit. In sloped tribal terrains, tree root systems anchor fragile topsoil, directly mitigating landslides and sheet erosion. Deep-rooted tree species like silver oak, deodar, and neem act as nutrient pumps, bringing subsoil minerals to the surface while providing windbreaks and additional revenue through timber, fodder and fruits. Alley cropping with oilseeds and legumes can also promote soil health.



Figure 1: Alley cropping of neem trees with pulses and oilseeds.

Rainwater Harvesting: Rainwater harvesting involves the storage of excess runoff water in man-made eco-reservoirs before it escapes the agroecosystem. In rainfed hilly areas, where

precipitation is high, constructing farm ponds, check dams, and micro-reservoirs allows farmers to maximise their water resource utility during dry spells or prolong the cropping period into the rabi season.



Figure 2: Ruza, a method of water harvesting system developed in the tribal hills of Nagaland.

Drip Irrigation: On sloped terrain where conventional flooding causes severe erosion and significant water loss, drip systems maximise water-use efficiency. By minimising evaporation and runoff, this method ensures the crop receives optimum moisture under limited water resources. Although the initial costs of setup can be high under such areas, the later results show greater productivity under sustainable amd climate resilient croppimg systems.

Organic Fertilizers:

Unlike high-efficiency chemical fertilizers that can leach rapidly during erratic rain on hillsides, organic fertilizers enhance soil aggregation, water holding capacity, and soil organic carbon content.

This fosters a robust soil microbiome, critical for sustaining long-term soil fertility and crop resilience. These fertilizers include vermicompost, FYM, green manure and biofertilizers to fix atmospheric nitrogen in high-altitude soils.

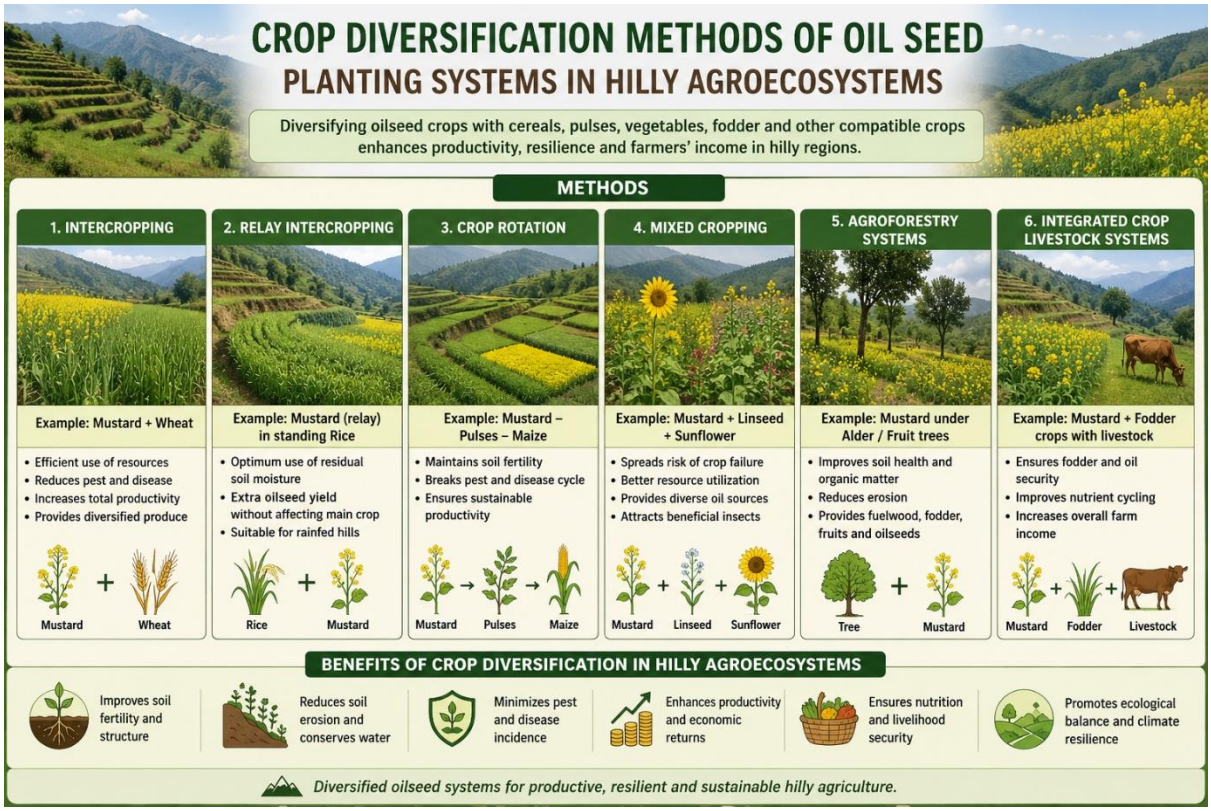


Figure 3. Represents different crop diversification methods for resilient oilseed cultivation.

Crop Diversification Methods:

Crop diversification involves shifting from monoculture toward complex cropping patterns like intercropping, sequential cropping, or mixed cropping. Growing multiple crop varieties simultaneously or in rotation spreads climate risks; if one crop fails due to a dry spell, another may survive. It also breaks pest cycles, balances nutrient use augmentation and enhances local food security. Popular methods proven to be successful are multitier intercropping of millets and pulses. The Wadi system, where orchard trees are grown alongside oilseeds. Agri-horti-Pastoral systems provide nutritional diversity for tribal families and their livestock. Contour farming is widely practised in regions like Koraput, Odisha, to secure yields against erratic rainfall and land degradation.

Minimum Tillage:

Traditional intensive ploughing on slopes accelerates soil breakdown and exposes vulnerable earth to heavy rainfall and wind. Reduced tillage minimises mechanical soil disturbance and retains crop residues on the surface, which shields the topsoil from erosion, enhances carbon sequestration and preserves natural soil structure and moisture. Zero tillage and conservation tillage practices can be practised under agroecosystems of hilly regions with low to no heavy mechanisation.

In tribal hills, these stewardship practices particularly address structural water stress and soil erosion. Integrated water resources management and water conservation are crucial. In these areas water conservation is necessary in ways like: Construction of contour trenches and contour bunds to slow runoff, building small ponds for use in the dry season, promoting agroforestry with native trees like *Acacia, Terminalia, Prosopsis*, *etc*., to stabilise slopes and prevent landslides.

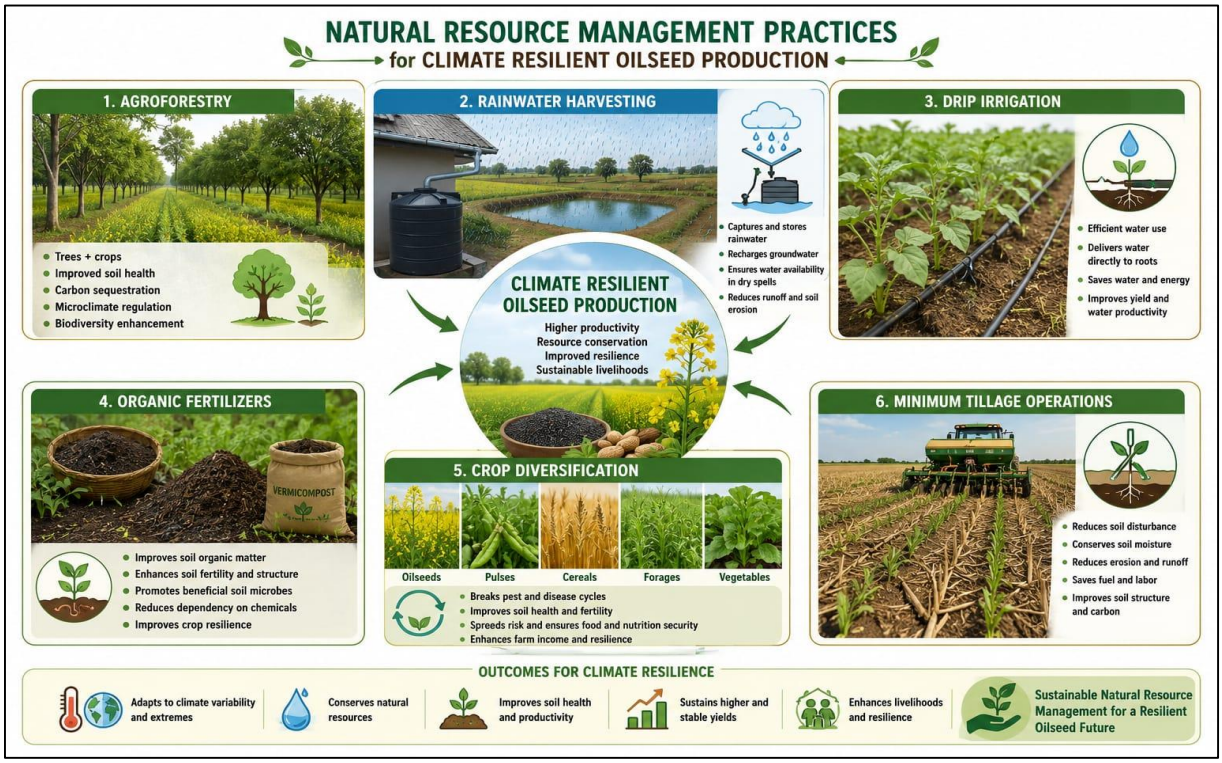


Figure 4: Represents Vital Natural Resource Management practices employed under oilseed production.

Natural Resource Management (NRM) strategies

Climate-resilient agriculture integrates sustainable practices to cope with climate extremes. These management practices include implementing water conservation, soil health, and agroforestry practices.

Table 2. Effective NRM practices are feasible in hilly tribal regions

NRM practices	**Working Mechanism**	**Benefits in hilly tribal areas**
Agroforestry	Alley cropping of trees with oilseeds on slops	Windbreaks, erosion control, and moisture retention
Rainwater harvesting	Pond/ trench system catches runoff and loses	Stores water for drought, prevents runoff losses, 30% more water for irrigation
Drip irrigation	Direct water application to roots, high WUE	Conserves scarce water resources, *i.e.* 50% water savings
Organic Fertilizers	Compost, FYM, Biofertilizers, Vermicompost application	Maintains soil fertility, restores soil organic carbon content
Crop Diversification	Growing sesame+ pulses+ millets together	Reduces crop failure risks, promotes natural soil replenishing ability
Minimum tillage	Conservation tillage and minimum tillage practices can be used.	Preserves the soil structure, reduces the usage of heavy machinery

Case Studies

Jawadhu hills, Tamil Nadu- a successful story of sesame crop by NRM practices:

Jawadhu hills are popular for their tribal farmers cultivating sesame. However, the major constraints for their marginal productivity are poor seed quality, almost no irrigation, and labour shortages. Major interventions were made in the years of 2023-2025 in different components of genetic improvement, NRM, and extension approaches. Drought-tolerant sesame varieties (JT-3, JRB-5) were introduced, more than 150 drip irrigation units were developed, 50 rainwater harvesting ponds were made, and over 200 farmer training sessions were conducted. The results were astounding with 51% growth in sesame yield, 47% increase in farmer income and 38% water utility.

Thus, through necessary interventions, the drought-tolerant varieties of oilseeds strengthened the agro ecosystem; developed irrigation infrastructure facilitated easy water resource accessibility, which in fact led to promotion of sesame-based agro industries for value-added linkages leading to growth in farmers' income and sustainability.

The Dongria Kondh Model- Niyamgiri Hills of Odisha:

In the Niyamgiri hill ecosystem, the indigenous Dongria-Kondh community successfully revived traditional oilseed cropping under natural agroforestry frameworks. Facing unpredictable monsoon spells, tribal farmers have integrated highly drought-resilient oilseeds like Niger and sesame as intercrops alongside millets on hilly terrains. By completely avoiding synthetic chemicals and incorporating biomass, these communities have devised a zero-input farming climate that protects the hilly slopes from nutrient leaching while achieving clean, high-value oil for tribal consumption and market supply.

NABARD's Integrated Tribal Development- Semi-Arid Hilly Terrains:

In degraded, hilly tribal pockets of India, the NABARD has introduced climate-resilient livelihoods centred around natural resource management. Tribal communities with fragmented, undulating lands implemented NRM structures like community ponds along the steps, semi-circular bunds, and organic contour farming. Farmers deliberately cultivated deep-rooted sunflower and sesame crops to stabilise the highly porous soil and act as natural soil tillers to break up heavy subsoil strata compaction. This structural system productively retains soil residual moisture, converting eroded, fallow areas into highly productive oilseed corners that secure small landholders against erratic seasonal droughts.

Recommended Actions: Collaborative efforts of reliable institutions

Achieving climate-smart oilseed production systems requires a collective effort and rapport between the regulating agencies with necessary actions. Accelerating the seed distribution system by partnering with ICAR-CRIDA and state agricultural universities to locate and employ climate-resilient varieties in tribal hilly regions. The establishment of community seed banks guarantees tribal farmers access to climate-smart seeds at hand. Properly funded breeding programs for extensive study on oilseed genomics, focusing on drought-tolerant traits, can help in fulfilling the aforementioned goals.

Scaling of NRM subsidies, such as providing 50-70% of cost sharing for trickle irrigation and rainwater reservoir augmentation. Conducting hands-on training for tribal farmers on natural farming and watershed conservation via Krishi Vikas Kendras. Integrating NRM works with MGNREGA schemes helps in generating income for tribal communities.

Scaling Framework and Policy Making: Necessary Government Interventions

- Achieving climate resilience goals requires coherent policies, which is an integration of agricultural development, environmental conservation, and rural linkage development strategies. Policymakers must develop a constitution of an oilseed improvement framework by leveraging the next generation of breeding tools.
- Short-term policy recommendations can include launching a tribal oilseed resilience mission targeting 10,000 tribal farmers with climate-smart seeds and NRM support; also subsidizing NRM infrastructure in tribal blocks and facilitating 500 or more seed banks across tribal districts for local seed availability.
- Medium-term policies can be formulated by focusing on plans such as integrating ICAR breeding pipelines with NRM programs, developing sesame/groundnut/niger-based

processing units in tribal hills for income diversification and scaling agroforestry by mandating 20% land under trees in hilly regions.

- Long-term planning must include a policy integration framework of linking agriculture, silviculture, IFS, sustainable environmental and rural development. Mapping climate resilient zones for oilseed suitability and funding for adequate research in 5-10 new oilseed genomes, focusing on required traits for cultivation in hilly regions under limited crop resources.

Conclusion

Climate resilient oilseed production in tribal hilly agro ecosystems hinges on synergizing genetic improvement with sustainable natural resource management. Biotechnological interventions and utilisation of indigenous germplasm for climate tolerance and yield enhancement should be our collective goal in achieving sustainable goals in the near future. Advanced breeding tools deliver stress- stable oilseed cultivars, while agri- silviculture, water harvesting, and soil conservation safeguard natural resources. Future efforts must prioritize on innovative approaches of policy integration, community building in tribal hills, ensuring food security and scaling location specific climate resilient technologies to secure oilseed production and elevate tribal livelihoods under climate change.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine
Volume 04, Special Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-10

LESS IN THE FIELD, MORE ON THE PLATE: WHY OILSEED NUTRITION DESERVES MORE ATTENTION

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Introduction

Walk into any kitchen in India and you will find an edible oil on the shelf. In the mustard-growing heartlands of West Bengal, Bihar, and Rajasthan, the sharp, pungent aroma of mustard oil defines the flavour of a meal. Travel south to Andhra Pradesh or Tamil Nadu and groundnut oil takes its place, providing the signature nutty and robust punch to the local cuisine. In Gujarat and Maharashtra, groundnut and sesame oils have been pressed from seed for centuries. In Karnataka and Kerala, coconut and sesame share the kitchen with newer entrants like sunflower. Move to Madhya Pradesh and Chhattisgarh, and soybean oil is now the most widely consumed vegetable oil in India by volume. Linseed, safflower, and castor round out a family of crops that, taken together, touch nearly every Indian plate, every single day, since time immemorial.

Yet India imports roughly 60–65% of its edible oil requirement, spending billions of foreign exchange every year on palm oil, soybean oil, and sunflower oil that could, with better agronomy, be grown at home. The paradox is not a lack of land, nor a lack of farmer interest, it is actually a persistent gap between what oilseed crops can yield and what they actually yield on most Indian farms.

The Yield Illusion

A farmer who has grown wheat knows the satisfaction of a heavy harvest, producing 4 to 5 tonnes per hectare on a good plot in the Indo-Gangetic plains, sometimes more. Rice performs similarly. Compare that with a mustard crop yielding 1.2 to 1.8 tonnes per hectare, or groundnut at 1.5 to 2 tonnes, or sunflower rarely crossing 1.5 tonnes, and oilseeds can look like a poor bargain.

But this comparison misreads what a crop is actually delivering. Yield in tonnes per hectare measures weight, not value and energy. When you ask how much food energy a crop produces per hectare, the picture changes dramatically.

Wheat grain carries roughly 3,300 to 4,100 kilocalories per kilogram. Soybean seed steps above this, delivering around 4,100 to 4,300 kilocalories per kilogram. Oilseeds such as groundnut and mustard climb further still, because fat, the primary storage compound in oilseeds is the most energy-dense macronutrient available in any food. A gram of fat contains more than twice the energy of a gram of starch or protein. Comparative analyses confirm that oil-containing seeds as a class average around 24 kilojoules per gram, compared to roughly 18 kilojoules per gram for cereals, a difference of nearly one-third. When the calculation is run across a full hectare, the energy gap between oilseeds and cereals shrinks dramatically. In the case of groundnut or sunflower, it can disappear entirely. The lower yield is not poverty, rather it is compression. Oilseeds pack more into every gram they produce. This energy density, combined with the essential fatty acids, fat-soluble vitamins, and protein that oilseeds deliver, makes them

nutritionally irreplaceable in the Indian diet. Improving oilseed productivity is therefore not merely an agronomic challenge. It is a public health and food sovereignty priority.

The Nitrogen Problem

Here lies a critical distinction that often goes unappreciated. The other nutritionally significant crop group, pulses like chickpea, lentil, and pigeon pea, carries its own fertiliser factory. Bacteria living in root nodules fix atmospheric nitrogen, reducing the pulse crop's dependence on soil nutrients and external fertiliser. A well-nodulated chickpea crop can fix 100 to 200 kilograms of atmospheric nitrogen per hectare essentially for free.

Oilseeds do not enjoy this privilege. With the partial exception of soybean, which does form a nitrogen-fixing symbiosis with *Bradyrhizobium* bacteria in its root nodules, crops like mustard, groundnut, sunflower, and sesame must source all their nitrogen from the soil or from applied fertilisers. They are entirely dependent on the nutrient capital of the field. Feed them poorly and the consequence is not just a smaller harvest, it is fewer calories reaching households, less oil in the supply chain, and a widening gap between what India grows and what India consumes.

This is precisely why nutrient management in oilseed crops is the foundation on which everything else rests.

Three Ways to Feed a Crop: What the Evidence Says

Indian farmers, researchers, and policymakers have debated the merits of chemical, organic, and natural farming for decades, often more loudly than the evidence warrants. Decades of field research across India, covering mustard, soybean, groundnut, sunflower, sesame, linseed, and other oilseeds offers a clear-eyed verdict on all three approaches.

Integrated nutrient management

Combining 50 to 80% of the recommended chemical fertiliser dose with organic amendments such as farmyard manure or vermicompost, and biofertilizers such as *Azotobacter*, phosphate-solubilising bacteria, or *Rhizobium* consistently delivers the highest or near-highest yields across virtually every oilseed crop tested. A mustard trial in Uttarakhand recorded 2,872 kg per hectare with 50% chemical fertiliser combined with vermicompost and *Azotobacter* outperforming full chemical fertiliser applied alone (Upadhyay et al., 2026). In Punjab, 75% of the recommended fertiliser dose combined with farmyard manure at 5 tonnes per hectare yielded 3,870 kg per hectare, with an excellent benefit-to-cost ratio (Kaur & Verma, 2023). Across soybean systems in the Himalayas, the 50% organic plus 50% inorganic combination produced the highest grain yield over seven years and built better soil in the process (Das et al., 2019).

Organic farming

Relying entirely on farmyard manure, vermicompost, neem cake, and biological preparations, performs respectably, but consistently falls 22 to 30% below integrated systems in most short-term comparisons. There is an important nuance, however. Multi-year studies of four to six seasons in soybean-based systems show organic management progressively narrowing this gap, sometimes eliminating it entirely, as soil organic matter builds and mineral nitrogen mineralises from the accumulating organic pool (Das et al., 2019). Soybean's own nitrogen-fixing ability is key to turn an organically managed soybean plot into a self-sustaining system. This convergence is not seen in mustard, sesame, or sunflower which crops have higher nutrient demands and no nitrogen-fixing ability.

In such crops the organic yield deficit persists even after multiple seasons (Sujatha et al., 2023).

Natural farming

Zero-budget natural farming (ZBNF), which relies on farm-prepared biological preparations such as Jeevamrit and Bijamrita rather than either chemical fertilisers or purchased organic inputs consistently produces the lowest yields in head-to-head comparisons across all oilseed crops. This is not a philosophical failing; it is a straightforward arithmetic one. Jeevamrit contains approximately 2% nitrogen and even smaller amounts of phosphorus and potassium (Praharaj et al., 2024). Oilseed crops removing 1,500 to 3,000 kg of grain per hectare need nutrient supplies that these preparations, applied at typical rates, simply cannot deliver. One study that partially bridged this gap did so by adding 50% of organic farming's manure inputs to natural farming practices and seed yields rose by nearly 20% as a result (Swathi et al., 2025). The lesson is that where soils carry high existing organic matter and fertility built over years of good management, natural farming performs better. Where soils are depleted and the nutrient gap is real, yield consequences are significant.

Again, it is to be noted that premium price of organically and naturally farmed oilseeds do compensate the lower yield associated with the systems. Making these two systems lucrative for the farmers.

The Special Case of Brassica Oilseeds

Mustard and rapeseed growers deserve a particular word about sulphur, zinc, and boron, the nutrients that separate a good Brassica crop from a great one.

Sulphur is not a micronutrient in mustard; it is almost as important as nitrogen. It is essential for the synthesis of glucosinolates and fatty acids that define mustard oil's quality, and studies consistently show 18 to 20% yield gains from adding sulphur at 20 to 40 kg per hectare within an integrated regime. Zinc and boron improve oil content and reduce anti-nutritional compounds. A recent trial using a multi-nutrient fertiliser providing potassium, sulphur, magnesium, calcium, and micronutrients simultaneously yielded approximately 600 kg per hectare more seed than a standard nitrogen-phosphorus treatment, and improved oil quality in the process. Neither organic amendments alone nor standard NPK formulations reliably deliver sulphur at the rates mustard demands in most Indian soils. The best-performing integrated treatments for Brassica almost universally include explicit sulphur supplementation alongside farmyard manure or vermicompost and a biofertilizer.

What Does This Mean for Soil?

There is a long-term story underneath the yield numbers that deserves equal attention. Purely chemical farming may sustain yields for several seasons, but long-term experiments tell a sobering tale: inorganic-only systems progressively deplete soil organic carbon, reduce microbial biomass, and lower the biological activity on which sustainable productivity depends. A 115-year permanent experiment at Tamil Nadu Agricultural University found soil organic carbon of 9.8 grams per kilogram under integrated management compared to 5.4 grams per kilogram in an unfertilised control, a difference accumulated over generations (Sridevi et al., 2024). Five-year studies consistently show that organic and integrated systems accumulate soil organic carbon and sustain microbial activity, while purely inorganic management leads to biological impoverishment even when short-term yields are maintained (Chitale et al., 2013; Narkhede et al., 2017).

This matters to a farmer not in abstract environmental terms, but in very practical ones: a soil rich in organic matter holds more water, releases nutrients more steadily, supports better root growth, and costs less to manage over time. The initial investment in building soil through farmyard manure, vermicompost, or crop residue incorporation pays dividends across decades.

The Bottom Line for the Farmer

For most oilseed crops, most soils, and most farming situations in India, the economically optimal and agronomically sound strategy is integrated nutrient management and not full chemical, not full organic, but a combination that brings together the best of both.

For mustard and rapeseed, this means 75 to 80% of the recommended fertiliser dose, combined with farmyard manure at 5 tonnes per hectare or vermicompost at 1 to 2 tonnes, *Azotobacter* or phosphate-solubilising bacteria as a seed treatment, and explicit sulphur supplementation (Upadhyay et al., 2026; Singh et al., 2019). This combination, documented across trials in Uttar Pradesh, Rajasthan, Uttarakhand, and West Bengal, achieves yields statistically equal to full chemical fertilisation while cutting chemical input costs by 20 to 25% and leaving the soil better than it was found.

For soybean, groundnut, and sunflower, the same principle holds, partial replacement of chemical inputs with organic amendments and biofertilizers consistently achieves the highest benefit-to-cost ratios, often outperforming both full-chemical and full-organic approaches in net returns per hectare.

The case for taking up oilseed cultivation is stronger than the yield numbers alone suggest. These crops produce more food energy per kilogram than most farmers realise, they command stable and often premium prices, and a well-managed oilseed plot improves the soil for whatever follows it in the rotation. India's edible oil import bill is a national challenge that farm-level agronomy can help solve with one well-fed mustard crop, one balanced groundnut plot, one carefully managed soybean field at a time.

The seeds are ready. The knowledge exists. The only question is whether the soil is fed well enough to let them do their work.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine
Volume 04, Special Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-11

CARBON FARMING APPROACHES IN RAPESEED-MUSTARD SYSTEMS: CAN OILSEED AGRICULTURE BECOME CLIMATE POSITIVE?

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Why carbon matters: rethinking in agriculture

Agricultural activities have traditionally been tightly connected with nature. The cultivation of plants requires rich soils, favourable climatic conditions, enough water and sustainable ecosystems. At present, global climate change has become one of the critical issues for agriculture that affects crop production and threatens global food security. Agricultural sector also has its contribution to the emission of greenhouse gases. This is done through land use change, intensive tillage, residue burning, and intensive fertilizer and fossil fuel usage. Due to this, many scientists and policy-makers seek to find innovative farm practices that could produce food and mitigate environmental issues at the same time.

One of such innovative farming practices is called carbon farming. It can be defined as such farm practices that would be aimed at capturing carbon dioxide from the atmosphere and storing it into soils and plant biomass while providing profit from the crop production. Rapeseed and mustard farming are increasingly viewed from the perspective of climate resilience, and not only crop productivity. In oilseeds production, carbon is important since it is directly related to the soil organic matter that is an essential element for soils in terms of fertility, moisture and nutrients.

Reconsidering rapeseed and mustard cultivation in the climate era mean shifting from practices that promote carbon loss to those that build and conserve soil carbon. These carbon-smart practices not only contribute to climate change reduction but also improve soil structure, enhance drought resilience, reduce dependency on input, and support stable yields. Here, carbon is no longer just an environmental indicator, it becomes a measure of agricultural sustainability and the future resilience of oilseed production systems.

From carbon source to carbon sink:

A carbon sink refers to any system that absorbs and stores more carbon than it releases. Rapeseed and mustard crops can support this process through their ability to capture atmospheric carbon dioxide while photosynthesis and transfer a part of that carbon into plant biomass and soil organic matter.

Excessive soil disturbance and intensive farming practices often accelerate the breakdown of soil organic matter, leading to the release of carbon dioxide into the atmosphere and contributing to climate change. However, rapeseed and mustard production systems have the potential to reverse this process by turning agricultural soils from carbon sources into carbon sinks. In recent years, carbon farming has emerged as an important approach for promoting sustainable agriculture. In rapeseed and mustard cultivation, practices such as improving soil carbon storage, reducing greenhouse gas emissions, and increasing resource-use efficiency help protect the

environment while supporting long-term productivity and soil health. These benefits make carbon farming a promising strategy for both climate change mitigation and sustainable crop production.

Can Every Mustard Field Become a Carbon Bank?

A carbon bank refers to an agricultural system that captures and stores atmospheric carbon while continuing to produce food and income. The idea of transforming every mustard field into a "carbon bank" seems ambitious, but it represents an important shift in modern agriculture. Rapeseed and mustard fields have the potential to contribute to this goal through practices such as conservation tillage, crop residue retention, balanced nutrient management, crop rotation, and improved soil health management. This could be done by increasing soil organic carbon and reducing greenhouse gas emissions that are unnecessary, these fields can gradually move from being carbon emitters to carbon reservoirs. However, to achieve this transformation at a large-scale farmer awareness is required, access to technology, supportive policies, and reliable carbon monitoring systems. While every field may not become a high-capacity carbon sink immediately, every small improvement in soil management can act as an investment toward healthier soils, greater resistance, and a more climate-responsible future for oilseed agriculture.

Carbon farming coming into practical action:

One of the most effective approaches is conservation tillage or minimum tillage. Excessive ploughing exposes soil organic matter to rapid decomposition, thus releasing stored carbon into the atmosphere. Farmers can conserve soil carbon, maintain moisture, and improve soil structure by reducing soil disturbance.

Crop residue retention is another important practice. Instead of burning mustard stalks and residues after harvest, retaining and incorporating them into the soil helps increase soil organic carbon and enriches nutrient availability. Microbial activity, which plays a key role in carbon stabilization which is encouraged by Residue recycling.

Crop diversification and crop rotation are equally important in carbon farming systems. Enhancement in biomass production, improved nutrient cycling, and reduced dependence on synthetic fertilizers can be achieved by rotating rapeseed and mustard with legumes or cereals. Legume integration contributes biological nitrogen fixation, thus lowering greenhouse gas emissions associated with nitrogen fertilizer use.

Efficient nutrient management is another practical strategy. The use of organic manures, compost, biofertilizers, and integrated nutrient management supports carbon accumulation in agricultural soils. Precision application of fertilizers by soil testing and balanced nutrient supply minimizes nitrogen losses and reduces emissions of nitrous oxide which is a potent greenhouse gas.

Water-saving irrigation practices also contribute to greener oilseed production. Maintaining optimum soil moisture helps support root growth and microbial processes involved in carbon sequestration. Methods such as drip irrigation and scheduled irrigation improve water-use efficiency and reduce the energy footprint of cultivation.

Modern technologies are increasingly strengthening the efforts in carbon farming. Remote sensing, digital advisory tools, and precision agriculture techniques enable farmers to monitor soil health, optimize inputs, and make climate-smart decisions at field level.

When we combine these practical approaches, it transforms rapeseed and mustard farming into a productive and environmentally responsible system. Carbon farming demonstrates that sustainable oilseed production is not only possible but essential for restoring ecosystems, improving soil resilience, and securing future food and nutritional demands.

Beyond yield:

Traditionally, agricultural success was measured mainly by crop yield. However, under changing climatic conditions and increasing pressure on natural resources, productivity alone is no longer enough. Carbon-smart rapeseed and mustard production emphasize environmental sustainability, efficient resource use, and long-term economic resilience alongside crop output.

Economically, carbon-smart management reduces dependence on synthetic fertilizers and improves resource-use efficiency, lowering production costs. Better soil quality also ensures stable yields and reduces climate-related risks, while emerging carbon markets may provide additional income opportunities for farmers.

Case studies:

To understand the practical realities of these carbon-smart frameworks, the following sections dissect key empirical data from recent institutional field trials.

Aspect	Experimental Location	Major Finding	Reference
Precision Nitrogen Management using GreenSeeker in Mustard	ICAR-Directorate of Rapeseed-Mustard Research	Green Seeker-based nitrogen application reduced N use and carbon footprint while increasing mustard yield by 19.3%.	Meena et al. (2024)
Cover Cropping & Biomass Carbon Sequestration in Brassica Systems	ple locations across th Asia and global ica-growing regions	Rapeseed–mustard biomass sequestration reached 0.3-1.2 t CO_2-e /ha/yr with improvements in soil organic matter and infiltration.	Jat et al. (2022)
Yield Gap Analysis and Impact Assessment of Rapeseed-Mustard through Cluster Front Line Demonstrations	Khowai District of Tripura, India	Resource-conservation practices increased yield by approx. 36.21% and improved B:C ratio under climate variability.	Sachan et al. (2023)
Tillage & residue management practices & crop rotation	Rajasthan	Using permanent raised bed with crop residue retention and crop rotation with maize Yield +142.9% high Profit +94% WUE +66%	Jat et al. (2021)

Challenges:

Carbon farming offers strong potential to reduce climate change impacts and improve sustainability in rapeseed–mustard systems, but large-scale adoption still faces challenges. A major limitation is the difficulty of accurately measuring and verifying changes in soil organic carbon (SOC), as carbon levels vary with climate, location, and management practices. Developing efficient Measurement, Reporting, and Verification (MRV) systems is essential for transparency and carbon-credit implementation.

Economic and institutional constraints also slow adoption. Carbon-smart practices often require initial investment, technical expertise, and long-term commitment before visible benefits occur. Smallholder farmers may be reluctant without financial incentives, extension services, and market support. Additionally, uncertainty in carbon pricing and policy frameworks continues to affect farmer participation and wider adoption.

Innovation:

Innovation is expected to play a transformative role in overcoming these constraints. Advances in precision agriculture, remote sensing, artificial intelligence, digital soil mapping, and soil carbon modelling are making carbon assessment more accessible and cost-effective. Emerging digital platforms can integrate weather, management, and soil information to support better farm-level decisions and improve carbon accounting accuracy. Looking ahead, carbon farming is likely to move beyond a standalone environmental practice and become an integral component of climate-smart oilseed agriculture. Future rapeseed and mustard systems may combine conservation agriculture, improved genetics, data-driven nutrient management, and carbon incentive programs to create productive and climate-resilient farming landscapes. Success will depend not only on storing more carbon but also on ensuring profitability, inclusiveness, and long-term ecological balance.

Conclusion:

Looking ahead, carbon farming is likely to move beyond a standalone environmental practice and become an integral component of climate-smart oilseed agriculture. Future rapeseed and mustard systems may combine conservation agriculture, improved genetics, data-driven nutrient management, and carbon incentive programs to create productive and climate-resilient farming landscapes. Success will depend not only on storing more carbon but also on ensuring profitability, inclusiveness, and long-term ecological balance. Carbon farming is therefore not the final destination but the beginning of a new agricultural transition - where healthy soils, resilient farmers, and climate responsibility grow together

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine
Volume 04, Special Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-12

SUSTAINABLE PLANT HEALTH MANAGEMENT IN OILSEED-BASED FARMING SYSTEMS

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Introduction

Oilseed crops like mustard, sesame, sunflower and soybean provide edible oil, animal feed and income for millions of small and marginal farmers, especially in tribal and hilly areas. These crops suffer losses from insects (aphids, pod borers, caterpillars), diseases (fungal, bacterial, viral) and weeds that compete for water, light and nutrients and can harbour pests and pathogens. Climate change is making pest and disease problems worse by shifting seasons, changing rainfall patterns and increasing extreme weather. Pests may appear earlier or move into new areas, and stressed plants become more vulnerable. Many farmers turn to chemical pesticides, but overuse pollutes soil and water, harms beneficial insects and people, and leads to pesticide resistance that reduces long-term effectiveness.

Sustainable plant health management reduces reliance on synthetic chemicals by combining practical methods: biological control (predators, parasitoids, beneficial microbes), eco-friendly pesticides, crop rotation, timely sowing, proper spacing, sanitation, resistant varieties and soil-improving practices like composting. Regular scouting, traps and weather-based forecasting help detect problems early and guide action only when economic thresholds are reached. Together these practices build resilient oilseed systems that protect yields, lower costs and environmental harm, and safeguard farmer and consumer health - especially important for smallholders in fragile hill and tribal landscapes.

NMEO, National Mission on Edible Oils – Oilseeds, it is a centrally sponsored initiative by the Government of India launched to boost domestic production and help the country achieve self-reliance in edible oils. It aims to increase primary production of major oilseeds, expand the cultivation area, boost yield and improve secondary extraction from secondary sources like cottonseed, rice bran and Tree-Borne Oils (TBOs).

Why plant health matters in oilseeds?

Oilseeds can achieve their full yield and oil-producing potential when they remain healthy throughout the growing seasons. Plants health influences crop growth, seed quality, oil content and market value. Oilseed crops are continuously threatened by a range of diseases and insect pests that reduce productivity and profitability. Important diseases include Alternaria blight and Sclerotinia stem rot in mustard, rust and tikka disease in groundnut, powdery mildew in sunflower and viral diseases such as yellow mosaic in soybean. These diseases damage leaves, stems, pods and seeds, ultimately affecting crop performance.

Insect pests further aggravate production losses. Mustard aphid (*Lipaphis erysimi*), whitefly, leaf miner, pod borer and cabbage caterpillar are

among the most destructive pests of oilseed crops. Their feeding activities reduce photosynthetic area, weaken plant vigour and impair seed development. Depending on the crop, pest species and environmental conditions, losses can range from moderate reductions in yield to severe crop damage during epidemic outbreaks. In mustard, fungal threats like Alternaria blight and Sclerotinia stem rot devastate harvests, triggering severe crop failures that can diminish yields anywhere from 30% to 80%. Similarly, groundnut productivity is severely compromised by rust and tikka disease, which together can cause devastating yield penalties ranging between 50% and 70%. Sunflower production faces major setbacks as powdery mildew restricts growth, causing yield losses that range from 20% to 50%. Meanwhile, the yellow mosaic virus remains a catastrophic hazard for soybeans, with early-stage infections capable of wiping out yields by as much as 85%.

The economic consequences of poor plant health extend beyond yield reduction. Farmers often incur additional expenditure on pesticides and other control measures, while poor-quality produce fetches lower market prices.

Maintaining plant health through sustainable and eco-friendly approaches is essential for improving productivity, ensuring livelihood security and promoting environmentally responsible oilseed production.

Eco-friendly crop protection strategies

Eco-friendly crop protection integrates biological, cultural, genetic, and soil health approaches to manage pests while minimizing environmental harm.



Figure 1: Sustainable Plant Health Management in Oilseed Crop

Biopesticides and biocontrol agents are central to eco-friendly crop protection: *Trichoderma viride/harzianum* control soil-borne fungal pathogens (*Fusarium*, *Rhizoctonia*) by colonizing roots and producing antibiotics; *Bacillus thuringiensis* (Bt) targets caterpillars and pod borers through toxic crystal proteins; neem seed kernel extract (NSKE) 5% acts as an antifeedant; Nuclear Polyhedrosis Virus (NPV) infects lepidopteran larvae fatally; and *Pseudomonas fluorescens* provides dual biocontrol plus growth promotion through phosphate solubilization and siderophore production.

Integrated Pest Management (IPM) modules from ICAR-IIOR for mustard/groundnut combine pheromone traps (5/ha for pod borer monitoring) with Economic Threshold Level (ETL) protocols ,spray only when pests exceed defined thresholds: aphids 5-10/terminal, defoliators 10% foliage damage, jassids 15-20/plant, *Helicoverpa/Spodoptera* 2 larvae/plant .Weekly Agro-Ecosystem Analysis monitors pest: defender ratios, activating control only when unfavourable (optimal 2:1).

Resistant/tolerant varieties offer genetic protection: ICAR-DRMR mustard lines (DRMRCI 172, DRMR 2018-25/BPM 1825, BPMQ 47, BPM 11) provide white rust resistance for Zones II-III with 40-42% oil content; ICAR-DGR groundnut varieties (ICG FDRS 10, ICGV 86590, R8808, R9201 resistant; GG 7, Girnar 4/5, VRI 2 moderately tolerant) combat rust/late leaf spot with high oleic acid variants yielding 37-57% over checks.

Cultural practices and soil health complete the approach: oilseed-cereal rotation breaks pest cycles reducing diseases 30-40%; intercropping (mustard+ chickpea 3:1, groundnut+ pigeon pea 3-6:1) reduces thrips/PBND; timely sowing avoids peak pest periods; seed treatment with bio-agents before sowing cuts disease 25-30%; vermicompost fortified with growth-promoting bacteria plus arbuscular mycorrhizal fungi enhances fertility, pathogen control, nutrient uptake (especially phosphorus), and disease/water stress resistance.

Eco-friendly practices

i. Habitat Management

Creating flowering strips, hedgerows, and refuge areas around fields encourages natural enemies such as ladybird beetles, lacewings, and parasitoids wasps, which naturally suppress pest populations and improve ecological balance.

ii. Push–Pull Technology

This strategy uses repellent plants within the crop and attractive trap plants around field borders. Pests are pushed away from the main crop and pulled toward trap crops, reducing damage without chemicals.

iii. Conservation Biological Control

Instead of introducing natural enemies, farmers protect existing beneficial insects by reducing broad-spectrum pesticides and maintaining diverse vegetation, allowing predators and parasitoids to regulate pest populations naturally.

iv. Precision Pest Monitoring

Digital tools, drones, remote sensing, and smart traps help detect pest outbreaks early. Timely interventions reduce unnecessary pesticide applications and improve the efficiency of eco-friendly pest management programs.

v. Bio fumigation

Certain plants such as mustard and radish release natural compounds when incorporated into soil. These compounds suppress soil-borne pathogens, nematodes, and weeds, improving crop health sustainably.

vi. Cover Cropping

Growing cover crops during off-seasons protects soil, suppresses weeds, conserves moisture, and

enhances beneficial microbial activity, creating conditions that reduce pest and disease pressure in subsequent crops.

vii. Induced Plant Resistance

Application of natural elicitors such as salicylic acid, chitosan, or seaweed extracts activates a plant's own defence mechanisms, enabling it to better withstand pest and pathogen attacks.

Environmental and economic benefits

Cutting down on chemical sprays protects more than just the crop. Mustard and sunflower depend heavily on bees for pollination, and heavy spraying kills off these pollinators along with the target pest - which means fewer flowers get pollinated and fewer pods form later. Less chemical runoff also means cleaner ponds, canals, and groundwater around farms, which matters a lot since the same water is often used for drinking and irrigation in rural areas.

On cost, it's better to be honest here instead of oversimplifying: biopesticides in India often cost more per hectare right now than chemical sprays, mainly because production is still small-scale and not as widely available. The real saving shows up later, not immediately. Chemical sprays need repeating again and again as pests build resistance over time, while biological methods, once used properly with correct IPM timing, need fewer repeat sprays. So, the benefit builds up over a season or two rather than showing up right away.

Soil response is the clearest and most direct win. Fields with lower chemical input consistently show better organic carbon levels and a stronger population of beneficial microbes, the kind that help plant roots absorb nutrients and resist disease on their own, naturally.

Adoption challenges

Despite the clear benefits, eco-friendly crop protection hasn't caught on widely yet, especially in remote farming pockets. In areas like Sambalpur and similar interior parts of Odisha, many farmers simply haven't heard of biocontrol options or don't fully trust them yet, since chemical sprays have been the default for generations.

Cost and availability add to the problem. Biopesticides aren't always stocked at the local agri-input shop the way chemical pesticides are, and when they are available, the price often puts off small and marginal farmers who are already working with tight margins.

Extension support matters more than people realize here. Krishi Vigyan Kendras (KVKs) are well placed to bridge this gap through field demonstrations and hands-on training, but their reach is still limited compared to the number of farmers who actually need this guidance. There's also a practical issue with the products themselves - many biopesticide formulations have a short shelf life, which makes storage and timely use difficult, especially in areas with patchy cold-chain or storage infrastructure.

Conclusion

India still buys most of its cooking oil from other countries, and that's not going to change if farms keep losing crops to disease, pests, and slowly tiring soil. Mustard, groundnut, sunflower - these are the crops that could actually close that gap, but only if they're protected the right way. Going eco-friendly here isn't some fancy upgrade or a trend to follow. It's basic sense. Biocontrol agents, IPM, crop rotation, better soil care - none of this is new science. Most of it has been tested and proven for years. The real problem has never been whether it works. It's whether it reaches the farmer standing in his field, deciding what to spray this season based on what his father always used. That's where the push needs to go now. More field demonstrations from KVKs, easier access to biopesticides, and a little

more trust built between scientists and farmers - and this shift stops being a "someday" plan and starts happening in real fields, this season.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine

Volume 04, Special Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-13

SECURING SUNFLOWER (*HELIANTHUS ANNUUS* L.) AGAINST EMERGING BIOTIC THREATS

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Introduction

Oilseed crops are 2nd most important crop after cereals, covering 14% of gross cropped area and contributing 75% of domestic vegetable oil production. Among oilseeds, Sunflower (*Helianthus annuus L.*) was grown as ornamental crop originally but now grown as oilseed crop, valued for high-quality edible oil, containing 40-52% oil and PUFA. Introduced to India in 1970 and became important for short duration (85-110 days), drought tolerant, and suitability for cultivation in different season. Besides oil extraction, sunflower seeds are also consumed as nutritious food, making crop economically significant. In recent year, Sunflower is promoted as summer crop in tribal areas under Mukhya Mantri Jana Jati Jeevika Mission (MMJJM) in Kandhamal district of Odisha. 500 tribal farmers across 46 villages cultivated sunflower on 200 acres in Phulbani, Khajuripada, Phiringia block. They successfully adopted sunflower cultivation as shown in figure1. after paddy harvest. ICAR-IIOR is expanding sunflower in NEH region - 1 lakh ha rice fallows available in Tripura alone. Early maturing 85-90 days hybrids suitable for NEH.

According to IPCC 6th assessment report, indicates global warming is likely to rise by 1.5-2.0°C by 2050, and hilly tribal regions are warming 1.5-2 times faster than plains due to elevation effect. Such warming is disrupting crop phenology, advancing or delaying sowing by15-20 days, results in upward migration of pests and pathogens to higher elevations that were absent before. All these changes causing ''emerging biotic stress''- new disease and pest outbreak. Long dry spell followed by heavy rainfall causes mite and leaf spot outbreaks. For tribal farmers far from KVK, one unexpected outbreak can damage 30-70% crop, as their traditional calendar is failing.

Although several studies have addressed plant biotic stress in plain areas, very few have developed surveillance and forecasting models for fragile hilly areas. Most existing models fail to access critical topographic factors such as slope, microclimatic variability. Hence, the present study is designed to develop low-cost, community-based surveillance, weather- based forecasting with eco-friendly management practices for emerging biotic stress in oilseed crops cultivated in tribal hilly region.



Figure1. Sunflower farming

1. Climate Change and Its Impact On Tribal and Hilly Agro-Ecosystem

Climate change is increasingly affecting tribal and hilly regions, where agriculture and livelihoods are highly dependent on natural resources and weather conditions. Rising temperatures, erratic rainfall patterns, and frequent extreme weather events have made these fragile ecosystems more vulnerable to environmental and agricultural stresses. In many hilly areas, changes in seasonal rainfall and increasing temperatures have altered the traditional cropping calendar which make farming activities less predictable. Water resources originating from mountain ecosystems are also under pressure due to changing hydrological conditions, leading to periods of both water scarcity and excessive runoff. These changes cause serious challenges to the sustainability of agriculture and food security in tribal communities.

The changing climate influence severity of biotic stresses such as insect pests, diseases, and weeds. Warmer temperatures are allowing several pests and pathogens to migrate into higher elevation that were previously restricted to lowland. Long dry spells followed by sudden heavy rains create favourable conditions for disease outbreaks such as blights, downy mildew, rusts, and other fungal infections. Likewise, drought conditions often trigger outbreaks of mites and thrips, while hailstorms and strong winds create wounds on plants that facilitate bacterial infections. Seasonal shifts have also altered the synchronization between crop growth stages and pest populations, resulting in the emergence of new pest problems and increased crop losses. Extreme climatic events such as floods, cloudbursts, landslides, hailstorms, and droughts have become more frequent in tribal and hilly regions and lack of proper irrigation facilities, lack of adequate infrastructure and technologies, poor transport and communication system causing severe damage livelihoods.

2. Sunflower Biotic Stress in Hilly Areas:

In hilly regions, sunflower production is affected by several biotic stresses caused by diseases and insect pests. Cool temperatures, frequent rainfall, high relative humidity conditions favour the development of fungal diseases such as Alternaria leaf blight, powdery mildew, downy mildew, rust, Verticillium wilt, Sclerotinia head rot, Phomopsis stem canker, and Rhizopus head rot.

Among these, as shown in figure2. Alternaria leaf blight causes severe defoliation, while Sclerotinia head rot and Rhizopus head rot directly damage flower heads and reduce seed yield and quality. Emerging diseases such as *Graphium euwallaceae* wilt have also been reported under moderate winter temperatures, indicating the increasing threat of new pathogens in sunflower-growing areas.

Insect pests are another major constraint in hilly ecosystems. Common oilseed pests as shown in figure3. such as aphids, whiteflies, leaf miners, tobacco caterpillar (*Spodoptera* spp.) attack sunflower at different growth stages. Aphids and whiteflies suck plant sap and transmit diseases, while caterpillars and leaf miners reduce photosynthetic area through leaf damage. Sunflower-specific pests including cutworms, stem weevils, root weevils, sunflower moths, seed weevils, and sunflower maggots attack stems, roots, leaves, flower heads, and developing seeds, leading to poor plant growth and significant yield losses. These pests may also reduce seed germination and cause metabolic imbalances in plants.

Therefore, sustainable sunflower production in hilly areas requires resistant hybrids, crop rotation, field sanitation, regular monitoring, biological control, seed treatment,

and need-based pesticide application as part of an integrated pest and disease management strategy.

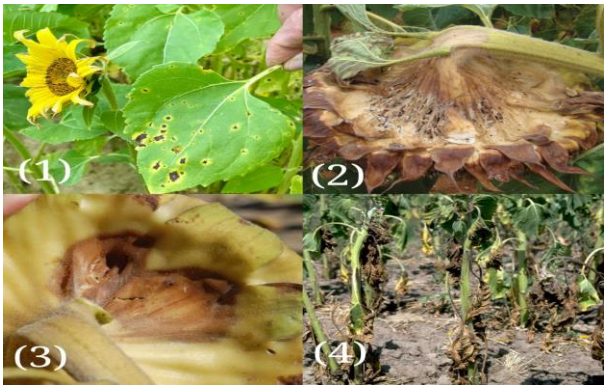


Figure2. (1) Alternaria leaf blight, (2) Sclerotinia head rot, (3) Rhizopus head rot, (4) Verticillium wilt

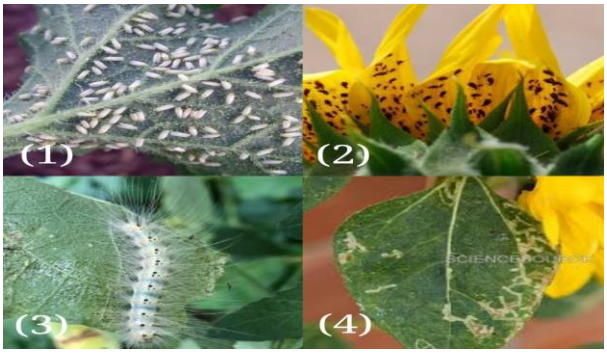


Figure3. (1) White fly, (2) Aphid, (3) Caterpillar, (4) Leaf minor

3. Surveillance Methods for Biotic Stress

Effective surveillance is the backbone of forecasting and management process. Surveillance is the systematic observation, monitoring and collection of data about the cultivated crop.

3.1. Conventional surveillance methods:

a. Field scouting: KVK/ department staff check 5-10 fixed fields every week. They note the % of infection in 20plants /field. Traditional methods are labourous, time taking and spatially constrained.

b. Pest trapping: Yellow sticky trap reduces highest aphid population (91.67%). Light trap for moths and pheromone trap for stem fly.

3.2. Modern surveillance methods:

a. GIS/GPS mapping: Geospatial technologies used for detecting and managing crop pests. Geographic Information System (GIS) and Global Positioning System (GPS) are powerful tools used for monitoring, mapping, and managing crop pests and diseases.

GIS helps in collecting, storing, analysing, and displaying spatial information related to pest incidence. GPS provides accurate location coordinates of infected fields. GPS-guided Variable Rate Technology allows pesticides to be applied only where needed. This enhances precision agriculture and sustainable crop protection.

Advantages:

- Early identification of infestation zones.
- Better resource allocation.
- Reduced crop losses.
- Area-wide pest management planning.

b. Unmanned Aerial Vehicles (UAVs) imagery: community scout flights drone over 10 acres. Drones equipped with red-edge sensors can detect disease symptoms before they are visible to the human eye. Research has shown that drone imagery can identify Alternaria leaf spot infections up to 5 days earlier than conventional visual scouting.

Advantages of Drone Surveillance:

- Rapid field coverage
- High-resolution images.
- Early detection of outbreaks.

- Reduced labor requirements.
- Supports site-specific pesticide application

c. Mobile apps: ''Kisan Suvidha", ''Plant Doctor", ''Plantix" - success AI apps detect disease/ pest by taking photo of affected crop.

Kisan Suvidha app developed by the Government of India, which provides weather forecasts, market prices, crop advisories, and pest management recommendations to helps farmers make timely crop protection decisions. Plant Doctor is a Mobile-based advisory platform. Farmers upload photographs of diseased plants and experts diagnose problems and recommend management practices. Plantix AI is an Artificial Intelligence-based disease diagnostic application. Farmers simply photograph affected plant parts. The app identifies diseases, nutrient deficiencies, and pest damage using image recognition technology and provides immediate recommendations for control measures.

Success Story of Plantix:

It is widely adopted by farmers in India and several other countries. Millions of plant images have been analysed through its AI system that enables rapid diagnosis even in remote areas lacking expert support. Helps in reducing yield losses through early disease detection.

d. Remote sensing (NDVI/EVI anomaly):

Normalized Difference Vegetation Index (NDVI) is a vegetation index used to assess crop health based on reflectance of red and near-infrared light. A 15% decline in NDVI or EVI (Enhanced Vegetation Index) often indicates plant stress before symptoms become visible.

Enhanced Vegetation Index (EVI) is more sensitive in dense vegetation than NDVI. Provides improved assessment of canopy structure and photosynthetic activity.

Benefits of Remote Sensing

- Large-area monitoring.
- Early warning of outbreaks.
- Reduced field scouting costs.
- Real-time crop health assessment.

4. Forecasting Methods for Plant Stress

Forecasting models using historical data predict future pest/ disease outbreak. The objective is to shift calendar based preventive spraying to need based and weather driven management, thereby reducing pesticide use and cost.

4.1. Weather based forecasting

Weather is the most important factor in disease development. Weather parameters like Temperature, Relative humidity, Rainfall, Leaf wetness duration, Wind speed, Soil moisture influence the life cycle of pathogen and provide them favourable condition to grow. Weather forecasts are integrated with disease models to issue warnings and recommend interventions.

Application in Sunflower

- High humidity (>80%) and moderate temperatures favor Alternaria blight. As shown in fugure 2.
- Prolonged leaf wetness promotes fungal infection.
- Rainfall and humidity can be used to forecast disease risk periods.

4.2. AI and ML based forecasting

AI tools like NASA harvest, combines high resolution earth data, weather information and historical outbreaks to create hyper local risk maps. Platforms like a where, merge satellite images with localized weather to forecast specific disease risk like fungal outbreaks.

Machine Learning (ML) algorithms are increasingly used for predicting crop diseases and pest outbreaks. The main objective of ML-based

forecasting is to provide early warning (forewarning) to farmers, helping them take preventive measures, reduce yield losses, and minimize excessive use of pesticides and fertilizers.

1. Artificial Neural Networks (ANN)

Artificial Neural Networks are the most widely used ML models in agricultural forecasting. Operate using the Gradient Descent algorithm, which minimizes prediction errors through iterative optimization.

Advantages:

- High prediction accuracy.
- Ability to handle large and complex datasets.

2. Support Vector Machines (SVM)

Support Vector Machines are the second most commonly used ML algorithms in disease forecasting. Effective in handling complex agricultural datasets.

Several studies reported that SVM models outperform ANN and traditional regression models in disease prediction.

3. Random Forest Technique (RFT)

Random Forest is an ensemble learning method based on multiple decision trees.

Advantages:

- High accuracy.
- Handles large datasets efficiently.
- Resistant to noise and missing data.

4. Recurrent Neural Networks (RNN)

- RNNs are specialized neural networks designed for sequential and time-series data. Similar architecture to ANN but with memory capability.

Advantages:

- Excellent for long-term forecasting.
- Captures changes in disease patterns over time.

4.3. Limitations in plant disease forecasting

- Data gaps: lack of high quality, comprehensive dataset that limits the overall accuracy.
- Forecasting relies on fixed assumptions, so it can fail when local environment changes.
- Most of the models are custom built for specific crops, so it's hard to use it broadly.
- Unpredictable temperature fluctuation and extreme weather alter the spread of pathogens, rendering older models less effective.
- Complex dynamics: pathogen interaction and behaviours with crop are difficult to fully map.

5. Management Methods For Plant Biotic Stress

5.1. IPM Recommendation

At high-risk alert, farmers are advised to

→ Instal yellow sticky traps for aphid monitoring @25traps/ha

→ Spray neem-based pesticide

→ Resistant hybrid DRSH-1 with 39.6% oil content + seed treatment Fluxapyroxad 1.5 g/kg followed by foliar Fluopyram 17.7% + Tebuconazole 17.7% @1ml/L. Gives lowest Alternariaster 7.36% and powdery mildew 4.52%. Yield 2124-2157 kg/ha.

5.2. Cultural and Biological controls

- Intercropping: Intercropping sunfllower with short duration legumes like (mungbean, soybean) at 1:2 or 2:1 row ratio, supported by marigold on border.

- Bioagents: farmers can use *Trichoderma and Pseudomonas* for seed and soil treatment to treat disease like root rot, especially in hilly regions. For active pests like aphids and stem fly, fungal bio pesticides such as *Beauveria bassiana* and *Metarhizium* are highly effective, particularly in high humidity areas like hills.
- Conserve natural enemies: don't kill Ladybird beetle, Chrysopa. Spray pesticides only at red alert zone.

5.3. Botanical control

a) NSKE/Neem oil: 5% NSKE controls emerging pests and fit organic farming.

Benefits of NSKE 5%

- Controls emerging pest populations before they reach damaging levels.
- Reduces dependence on synthetic insecticides.
- Delays development of pesticide resistance.
- Environmentally safe and biodegradable.

b) Manual spray is difficult and uneven at hilly regions, so can use drone for slopes (70% less chemical with uniform coverage.

For sunflower grown in hilly regions, drone spraying:

- better canopy penetration.
- Enables timely application during disease outbreaks.
- Reduces wastage of chemicals.
- Supports precision agriculture practices.

c) ETL based spray: Economic threshold level (ETL) defines the specific pest population density at which control measures must be applied to prevent damage.

Importance of ETL:

- Avoids unnecessary pesticide application.
- Reduces production costs.
- Conserves natural enemies.
- Prevents pesticide resistance development.
- Minimizes environmental pollution

Conclusion

This study shows that climate change is changing how pests and diseases attack sunflower in the hilly tribal area. Alternaria blight and aphids are now showing of earlier and spreading faster mainly when nights got warmer and humidity went up during the crop's sensitive growth stage. This means the weather is shifting, and that’s giving new diseases a chance to grow. The old ways of farming and spraying pesticides blindly don't work anymore here. On slopes, rain washes away chemicals, pollutes water resulting the tribal farmers can't afford repeated sprays. So, low-cost IPM plan made specifically for these hills. Use resistant seed varieties, treat seeds with friendly fungi like *Trichoderma*, put up yellow sticky traps and spray chemicals only when the pest crosses the danger level-called ETL.

Most importantly, by using mobile apps the whole village should monitor crops together that's the way we can catch the problem early, 10-15 days before any real damage.

Going forward, we need weather-based warning system for farmers and IPM modules tested for other oilseeds like Niger and Soybean too. If we focus on healthy soil and good seeds, our hills can still grow strong crops even as the climate changes.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine

Volume 04, Special Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-14

GREEN SHIELD FOR GROUNDNUT: BOTANICAL FORMULATIONS FOR MANAGING SUCKING AND LEPIDOPTERAN PESTS

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Introduction

Groundnut (*Arachis hypogaea* L.), commonly known as peanut or earthnut, is one of the world's most important oilseed and food legume crops. The seeds contain approximately 48–50% edible oil, 26–28% protein, and essential vitamins and minerals, making groundnut an important source of nutrition and income for millions of farmers. India is the second-largest producer of groundnut after China, with major cultivation concentrated in Gujarat, Andhra Pradesh, Tamil Nadu, Karnataka, Telangana, Maharashtra, and Rajasthan.

Despite its economic significance, groundnut productivity in India remains lower than the global average due to several biotic, abiotic, and socioeconomic constraints. Among the biotic factors, insect pests are a major concern, causing approximately 15% yield loss and substantial economic damage. More than 360 species of insects and mites have been reported to infest groundnut, among which defoliators such as the groundnut leaf miner, tobacco caterpillar, gram pod borer, and hairy caterpillars, as well as sap-sucking pests including aphids, leafhoppers, and thrips, are particularly destructive (Fig 1)

Management of these pests largely depends on synthetic insecticides; however, their indiscriminate use has led to problems such as resistance development, pest resurgence, environmental contamination, and pesticide residues in harvested produce. Consequently, there is an urgent need for safe, effective, and environmentally sustainable alternatives. Plant-derived bioactive compounds, including alkaloids, terpenoids, phenolics, flavonoids, and steroids, have demonstrated considerable potential for insect pest management. Botanical extracts and formulations have been widely investigated for their insecticidal, repellent, and antifeedant properties.

(a)





(b)





(c)





Fig 1. Major insect pests of groundnut

(a) groundnut leafminer, *Aproaerema modicella*; (b) groundnut aphid, *Aphis craccivora*; (c) tobacco caterpillar, *Spodoptera litura*

Global Biopesticide Market Size

The global biopesticide market has expanded rapidly, with its share of the crop protection market increasing from 3.5% in 2009 to 5% in 2021. Fruits and vegetables account for the largest share of biopesticide use (18%), while bioinsecticides comprise 27.9% of the global biopesticide market. Europe and North America each hold more than 30% of the regional market share, whereas Latin America is the fastest-growing market. Despite the increasing adoption of biopesticides worldwide, their market share in India remains relatively low at 4.2%. More than 390 biopesticides have been registered in the USA and about 970 in India. Among botanical biopesticides, neem- and pyrethrin-based products dominate the market, with sabadilla, tobacco, ryania, and, more recently, essential oil-based insecticides also gaining commercial importance. Some commercially available botanical formulations are listed in Table 1.

Table 1. Commercially available botanical pesticides

Active Ingredient	**Application**	**Commercial Product**	**Company**
Oil of neem (Azadirachtin)	Insecticide	Margosom®	Agri Life (Telangana, India)
Oil of neem (Azadirachtin)	Insecticide	AZA-Direct R®	Gowan Company (Arizona, USA)
Oil of neem (Azadirachtin)	Insecticide	Azera TM®	MGK (Minnesota, USA)
Oil of neem (Azadirachtin)	Insecticide	Azamax ®	UPL Ltda. (Campinas, Brazil)

Oil of neem (Azadirachtin)	Insecticide	Molt-X®	BioWorks Inc. (NY, USA)
Oil of neem (Azadirachtin)	Insecticide	Neemix 4.5®	Certis (Columbia, USA)
Oil of neem (Azadirachtin)	Insecticide	Azatin XL®	OHP Inc. (SC, USA)
Oil of neem (Azadirachtin)	Insecticide	NeemAzal T/S®	Trifolio-M (Lahnau, Germany)
Oil of neem (Azadirachtin)	Insecticide	Fortune Aza 3% EC®	Fortune Biotech (AP, USA)
Oil of neem (Azadirachtin)	Insecticide	Shubhdeep NeemOil®	King AgroFood (Haryana, India)
Essential oil of garlic (*Allium sativum* L.)	Insecticide	AjoNey®	I.H.N. (Mexico)
Essential oil of garlic (*Allium sativum* L.)	Insecticide	EcoA-Z®	EcofloraAgro (Antioquia, Colombia)
Essential oil of garlic (*Allium sativum* L.)	Insecticide	L'EcoMix®	EcofloraAgro (Antioquia, Colombia)
Essential oil of garlic (*Allium sativum* L.)	Insecticide	CapsiAlil®	EcofloraAgro (Antioquia, Colombia)
Citrus sinensis L. oil (limonene and linalool)	Insecticide/ repellent	Demize EC®	Paragon Professional Pest Control Products (Tennessee, USA)
EO of thyme (*Thymus vulgaris*)	Insecticide /repellent	Prev-Am®	Oro Agri SA Ltd. (South Africa)
EO of thyme (*Thymus vulgaris*)	Insecticide /repellent	EcoVia WD®	Rockwell Labs Ltd. (North Kansas City, USA)
Rotenone	Insecticide	5% Rotenone ME®	Beijing Kingbo Biotech Ltd. (Beijing, China)
Rotenone	Insecticide	Rotenone Dust®	Bionide Products Inc. (NY, USA)
Nicotine (*Nicotiana tabacum* L.)	Insecticide	Nico Dust®	Nico Orgo Manures (Gujarat, India)
Nicotine (*Nicotiana tabacum* L.)	Insecticide	Nico Neem®	Nico Orgo Manures (Gujarat, India)
Nicotine (*Nicotiana tabacum* L.)	Insecticide	10% Nicotine AS®	Beijing Kingbo Biotech Ltd. (Beijing, China)
Carvacrol/EO of oregano (*Origanum vulgare*)	Insecticide/ animal feed supplement	By-O-reg+®	By-O-reg+ (SD, USA)

Botanical formulations for managing groundnut pest

A field experiment conducted by Abarna et al. (2019) during Kharif 2017–2018 at Aruppukottai, Virudhunagar, Tamil Nadu, India, evaluated the efficacy of various botanical treatments against the groundnut aphid, *Aphis craccivora* (Hemiptera: Aphididae), under rainfed conditions. The treatments included *Acorus calamus* (2%), neem oil (3%), karanji oil (3%), *Calotropis gigantea* (5%), *Nerium indicum* (5%), *Azadirachta indica* (5%), *Vitex negundo* (5%), neem seed kernel extract (NSKE, 5%), and chlorpyrifos 20 EC (2.5 mL L^{-1}). Among the botanicals, NSKE at 5% recorded the highest suppression of *A. craccivora* (67.9%) compared with the untreated control, followed by neem oil at 3%, which achieved 65.2% suppression.

Ghosh (2020) assessed the efficacy of several biopesticides against *A. craccivora* infesting groundnut. The treatments comprised the microbial toxin *Saccharopolyspora spinosa* (Spinosad 45 SC), extracts of tobacco leaves (*Nicotiana tabacum*) and floral parts of *Polygonum hydropiper*, and azadirachtin (Nimbicidine 1500 ppm), which were compared with imidacloprid (Confidor 17.8 SL). Imidacloprid provided the highest aphid suppression (85.47%), followed by azadirachtin + tobacco extract (79.94%) and imidacloprid + *Polygonum* extract (79.18%). Among the biopesticides, mixed formulations of azadirachtin + *Polygonum*, spinosad, azadirachtin alone, tobacco leaf extract, and *Polygonum* floral extract achieved moderate to high aphid suppression of 76.09, 75.07, 71.77, 57.59, and 55.35%, respectively.

The efficacy of an oil-based formulation (OF) and an aqueous formulation (AqF) against sucking and lepidopteran pests of groundnut was evaluated in a randomized block design with seven treatments and three replications (Singh et al. 2024). Treatments included OF and AqF at 10 and 20 mL L^{-1}, chlorpyriphos 20 EC (2.5 mL L^{-1}), neem oil (3 mL L^{-1}), and an untreated control. Chlorpyriphos recorded the highest suppression of whiteflies (92.8%), leafhoppers (90.3%), thrips (84.7%), and red hairy caterpillars (82.9%). Among the botanicals, AqF at 20 mL L^{-1} consistently showed superior efficacy, reducing whiteflies, leafhoppers, thrips, and red hairy caterpillars by 80.0, 83.1, 76.9, and 80.8%, respectively, followed by OF at 20 mL L^{-1}. Overall, both formulations at 20 mL L^{-1} performed at par with or better than neem oil applications.

Mode of action of botanical formulations

Botanical insecticides exert multiple modes of action across different developmental stages of insects (da Silva Sá, et al. 2023). During immature stages, they can damage the egg exocorionic network, disrupt embryonic development by interfering with chitinization, impair larval morphology, alter digestive tract epithelium and enzyme expression, reduce larval mobility, and damage the external surfaces or respiratory system of pupae, thereby affecting normal pupal development. In adults, botanical insecticides may induce incomplete ecdysis and impair olfactory perception, feeding behaviour, and reproductive functions. Owing to these diverse mechanisms, broad-spectrum botanical insecticides have considerable potential for managing insects across their entire life cycle.

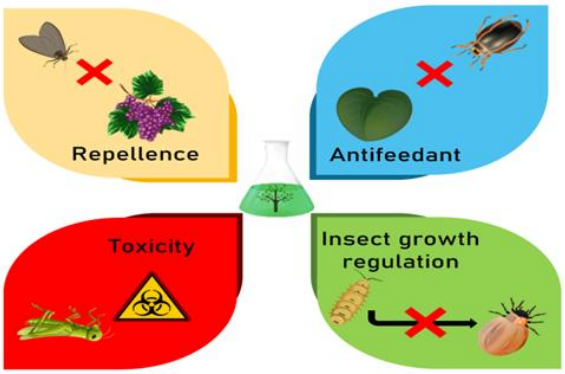


Fig 2. Mode of action of botanical pesticides

Merits of using botanical formulations

The botanicals offer several advantages such as ecologically beneficial, low toxicity toward nontarget organisms, typically biodegradable, and not readily prone to developing resistance in insects because of their multiple modes of action and the complex nature of their chemical components (Guo et al. 2023; Lengai et al. 2020).

Conclusion

Botanical formulations offer an effective, eco-friendly, and sustainable approach for managing major sucking and lepidopteran pests of groundnut (*Arachis hypogaea* L.). Their insecticidal, repellent, and feeding-deterrent properties can significantly reduce pest populations while minimizing the adverse effects associated with synthetic pesticides. Incorporating botanical formulations into groundnut pest management practices can enhance crop protection, conserve environmental quality, and support sustainable agricultural production.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine
Volume 04, Special Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-15

ECO-FRIENDLY PLANT HEALTH MANAGEMENT FOR OILSEED FARMING IN INDIA'S FRAGILE TRIBAL AND HILLY LANDS

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Introduction

Oilseeds are agricultural crops grown primarily for the extraction of edible or industrial oils from their seeds. These oilseeds are used in cooking, food processing and industrial applications. Common oilseeds include soybeans, sunflowers, rapeseed, sesame, flaxseed and peanuts. Oilseed crops are the second most important determinant of agricultural economy, next only to cereals. The oilseed crops are not only important for cooking but also used in various industrial applications, including the production of biodiesel, animal feed, and cosmetics. Furthermore, oilseeds contribute to sustainable agriculture practices by enhancing soil fertility and providing rotational options for farmers.

In India's hilly and tribal regions, communities cultivate a mix of traditional annual oilseeds like Niger, mustard & sesame and wild tree borne oilseeds like mahua, Sal and karanja . In the tribal areas of Odisha tree borne oilseeds are the type of NTFP (Non-Timber Forest Product) which are abundant but their potential arguably remains untapped which include Sal, Kusum , Karanj, Neem, Mahua , Castor. Oil of these seeds are used for medicinal purposes and to treat skin conditions, others for cooking or as a fuel , while others are ingredients in food products. Niger is called the "lifeline of tribal agriculture and economy ".

Pests, diseases, weed and their management in oilseeds

Oilseeds are damaged by several pests; including mustard Aphids *(Lipaphis erysimi)* , Bihar hairy caterpillar *(Spilosoma obliqua)* , Niger capsule fly *(Dioxyna sororcula),* sesame webworm *(Antigastra catalaunalis)* , etc. In these hilly areas high humidity, frequent rainfall and poor drainage provide a favorable environment for the development of many diseases resulting in severe yield loss. Some of the common dangerous diseases include *Alternaria* blight, white rust *(Albugo candida),* downy mildew *(Hyaloperonospora brassicae),* sesame phyllody *(Candidatus Phytoplasma),* leaf spots (Cercospora), etc. Common weeds found in these areas include bathure (*Chenopodium album)* little seed canarygrass (*Phalaris minor)*, wild oat (*Avena ludoviciana*), nut sedge (*Cyperus rotundus*) and scarlet pimpernel (*Anagallis arvensis)*.

Integrated Pest, Disease and Weed Management (IPDWM)

It is a sustainable approach that helps in protecting the oilseed crops from pests, diseases, and weeds while reducing sole dependence on chemical pesticides. In hilly regions, effective IPDWM begins various culture practices like selecting well-drained fields, using resistant or locally adapted varieties, practicing deep summer ploughing, and maintaining proper drainage through raised beds and contour bunds. Crop rotation with cereals and legumes, inter cropping

timely sowing, optimum plant spacing, and the use of healthy, disease-free seed help reduce pest and disease incidence. Regular field sanitation, removal of infected plant debris, and timely weed control are also essential for maintaining a healthy crop environment.

A combination of biological and mechanical methods further strengthens pest management. Bird perches, light traps, sticky traps, and pheromone traps can be installed to monitor and suppress pest populations naturally. The yellow sticky traps as shown in Fig 1, are low cost and farmers can easily afford it. This yellow sticky traps are used to attract the air borne pests and hence they easily control the pest infestation. Conservation and use of beneficial organisms or biological control agents such as parasitoids predators, plays an important role in keeping pests under control. Eco-friendly biopesticides, including neem-based products, neem seed kernel extract (NSKE), and beneficial fungi such as *Beauveria* and *Metarhizium*, can also be used as part of biological control strategy. Chemical pesticides should be applied only when pest populations exceed economic threshold levels, ensuring sustainable oilseed production while protecting biodiversity, soil health, and farmer safety.



Fig.1: Sticky Trap for Insects Pests Monitoring

Forecasting and managing biotic risks in oilseeds:

Climate change is inevitable owing from modern-day chemical agriculture, exerting detrimental impacts on sustainable crop production. Global agriculture is now facing serious threats from biotic stresses like weeds, pests, diseases, etc. Crops are vulnerable to several biotic stressors and unfavorable environmental conditions that can affect their growth and development resulting yield loss. 'Biotic stress' refers to the damage that plants suffer from living organisms such as pests, parasites, bacteria, fungi, nematodes, insects, and viruses. Biotic stress can lead to yield losses of rapeseed and mustard 19.9%, soybean 26.3% and 83% seed yield reduction when left uncontrolled in sesame.

Chemical fungicides, herbicides, and insecticides that effectively control diseases, weeds, and pests have shown to be harmful to the environment and to human health. In addition to their accumulation of chemicals pesticides residues over period of time in environment cause detrimental effects on non-target organisms . For instance, herbicides are more successful in eradicating uncommon plant species than weed species. To reduce pesticide use, safer alternatives must be used.

1.1 Forecasting Biotic Threats:

It is becoming increasingly important for sustainable oilseed production, particularly in hilly regions where climate variability can significantly influence pest and disease dynamics. Predictive crop-weather models can be used to understand and forecast the occurrence of major insect pests by linking their life cycles and population growth patterns with weather parameters such as temperature, rainfall, humidity, and wind movement. Geographic Information System (GIS), this based

zonation further strengthens pest forecasting efforts in mountainous ecosystems. Hilly terrains exhibit considerable variation in altitude, slope, temperature, and moisture conditions, creating diverse microclimates that influence pest distribution. By combining spatial data on climate, topography, cropping patterns, and historical pest incidences, GIS tools can identify vulnerable zones and map potential shifts in pest habitats.

1.2 Management Of Biotic stress (Organic ways to mitigate biotic stresses)

The use of several cultural practices, such as mulching, multiple crops, flowering and nectar plants, trap crops, and cover crops, can effectively control many biotic stresses. Careful and continuous monitoring of pest and disease infestations at critical stages of a crop's growth is key to efficient management. Physical and mechanical methods include the use of traps, baits, manual, and mechanical options to control the biotic stresses. For instances, manual collection of insects and larva, uprooting plants and destroying diseased parts, clipping off of the pest and disease infested leaves, hand weeding, hand hoeing, wheel hoeing, spudding, digging, chaining, flaming/burning weeds, soil solarization, etc., all play a role in reducing biotic stresses. Cultural control is about modifying the environment, improving the health of host, or modifying the pest's behavior to mitigate or prevent infestation. Crop rotation, crop and variety selection, sowing time, spacing, seed rate, time of harvesting, irrigation and nutrient management, tillage, mulching, intercropping, stale-seedbeds, summer fallow, and the use of trap crops all contribute to reducing populations of weeds, pathogens, insects, mites, and other pests in agricultural crops. Soil solarization is an effective ecological method to control weeds, soil, or seed-borne insect pest issues by covering the soil with a transparent polythene film. Certain varieties are better adapted to the soil moisture, space, air, and light than weeds due to their weed tolerance and ability to suppress weeds. As a result, they develop faster, outcompete weeds, and yield a greater quantity.



Fig.2: Sustainable Agriculture Practice

As mentioned in fig 2, sustainable agricultural practices not just protects the plant health but it also helps in improving and protecting the soil health by soil conservations, soil moisture maintenance, prevention of soil erosion and improving soil fertility. Overall sustainable agriculture provides a healthy ecosystem for the growth of the oilseeds in hilly terrain.

Organic farming is a sustainable farming system that relies on natural processes and eco-friendly practices to maintain soil health, crop productivity, and environmental balance. It reduces the use of synthetic fertilizers and pesticides, promotes biodiversity, and helps conserve natural resources. By improving soil fertility and supporting beneficial organisms, it enhances the resilience of agricultural systems against pests, diseases, and climate-related stresses. Although it may face certain challenges, organic farming contributes to safe food production, environmental protection, and long-term agricultural sustainability. Therefore, it is considered an important approach for achieving a healthier and more sustainable future. It is the best approach as it is cost effective and can be done by all the farmers.

Ecological Approaches to protect oilseeds in hilly tribal terrains

Management of pests is crucial for protecting the crops to minimize the yield losses. Since the 1960s, pest control has relied on chemical pesticides which have led to numerous negative externalities, including unintended effects on human health and changes to biodiversity.

In hilly regions, effective pest and disease management in oilseed crops should be closely linked with soil and water conservation practices. Since sloping lands are highly vulnerable to soil erosion and runoff, adopting contour farming and terracing helps retain topsoil, conserve moisture, and create a more stable environment for crop growth. Diversified cropping systems such as intercropping oilseeds with non-host crops can reduce pest movement and limit the spread of infestations. Similarly, the use of trap crops, such as marigold around mustard fields, attracts insect pests away from the main crop and reduces damage. Integrating agroforestry practices by planting perennial shrubs or trees along terrace boundaries further strengthens the farming system. These vegetation barriers act as windbreaks, reduce erosion, and provide shelter for beneficial insects and predatory birds that naturally help control pest populations. Together, these agroecological approaches enhance the sustainability and resilience of oilseed cultivation in hilly terrains.

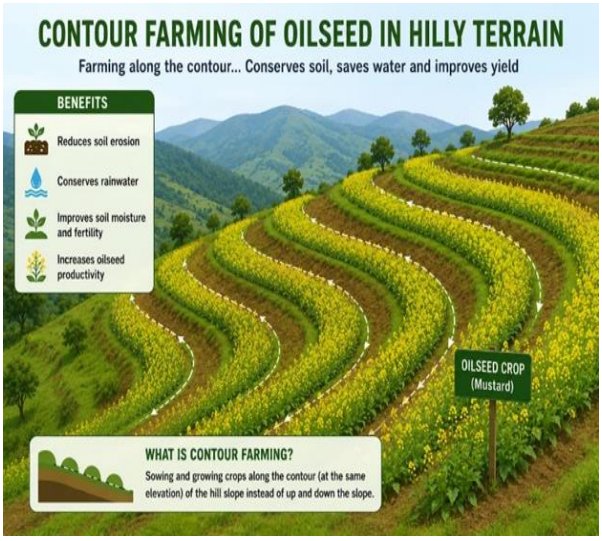


Fig.3: Practice of Contour Farming in Hilly Terrain

Biological control agents play an important role in the sustainable management of diseases and insect pests in oilseed crops, particularly in environmentally sensitive hilly regions. Among the most widely used bio-agents, *Trichoderma viride* and *Trichoderma harzianum* are applied as seed treatments or soil amendments to suppress soil-borne pathogens

responsible for root rot, damping-off, and wilt diseases. These beneficial fungi not only inhibit pathogen growth through competition and parasitism but also promote root development and nutrient uptake. Similarly, *Pseudomonas fluorescens* colonizes the rhizosphere and protects plants against several fungal pathogens by producing antimicrobial compounds and inducing systemic resistance in the host plant. In addition, beneficial microorganisms such as *Azotobacter* and *Azospirillum* improve plant vigour and stress tolerance, indirectly increasing resistance to pest and disease attacks. Predators are free living organisms that actively hunt, capture, and consume large numbers of pest species across their lifecycles. Common examples include lady beetles, lacewings, and predatory mites that feed on aphids and caterpillar. Parasitoids are insects (such as tiny parasitic wasps) that lay their eggs inside or on the body of a host pest. Once hatched, the developing larvae consume the host from the inside out, ultimately killing the pest. Microbials are naturally occurring bacteria, fungi, viruses, and nematodes that infect and cause fatal diseases in specific target pests. A highly utilized example is the soil bacterium *Bacillus thuringiensis (Bt),* which produces proteins that are toxic only to specific insect larvae while remaining completely safe for humans, pets, and beneficial pollinators. These all helps us not to rely on harmful chemicals for pest management.

Natural farming relies on locally available biological inputs to improve soilhealth, plant growth, and pest management. Beejamrit, prepared from cow dung, cow urine, lime, and water, is used as a seed treatment to protect seeds from pathogens and enhance germination. Jeevamrit, a fermented mixture of cow dung, cow urine, jaggery, pulse flour, and soil, enriches microbial activity and improves nutrient availability in the soil. For pest management, farmers use botanical formulations such as Neemastra, which acts as a natural repellent and growth regulator against sucking pests. These low-cost and eco-friendly inputs strengthen plant immunity, reduce dependence on chemical pesticides, and support sustainable oilseed cultivation in hilly regions.

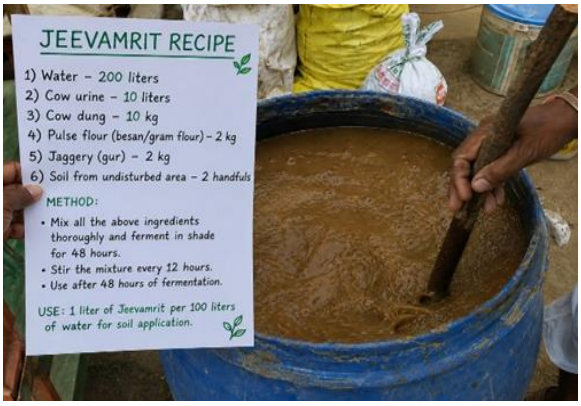


Fig 4: Preparation of Jeevamrit

Conclusion:

Oilseed crops are crucial for food security, nutritional well-being, and the livelihoods of tribal communities in hilly regions, where they support income generation, traditional practices, and local economies. However, high humidity, poor drainage, frequent rainfall, and the increasing impacts of climate change create favorable conditions for weeds, pests, and diseases, leading to significant reductions in yield and quality. To address these challenges sustainably, the adoption of integrated pest, disease, and weed management strategies supported by agroecological approaches is essential. Practices such as selecting well-drained sites and resistant varieties, crop rotation, timely sowing, improved drainage, intercropping, mulching, trap cropping, conservation of natural enemies, use of biological control agents, natural farming inputs, and climate-informed surveillance and forecasting tools can effectively reduce biotic stresses while minimizing dependence on synthetic pesticides.

Strengthening these environmentally friendly and cost-effective management practices not only enhances crop resilience and productivity but also protects human health, conserves biodiversity, improves livelihood security, and promotes climate-resilient and sustainable oilseed farming systems in hilly ecosystems.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine
Volume 04, Special Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-16

WEED MANAGEMENT IN RAPESEED AND MUSTARD

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Introduction

Rapeseed and mustard are among the major oilseed crops grown for edible oil production. These crops play an important role in agriculture and contribute significantly to farmers' income. However, one of the major constraints affecting their productivity is weed infestation. Weeds compete with crop plants for essential resources such as nutrients, water, sunlight, and space, resulting in poor crop growth and reduced yield.

Weed management is therefore an important cultivation practice to ensure healthy crop establishment and maximum productivity.

Importance of Weed Management

During the initial growth stages, rapeseed and mustard plants grow relatively slowly, making them vulnerable to weed competition. Weeds absorb soil nutrients and moisture more efficiently than crop plants and may suppress crop growth.

The critical period of weed competition in rapeseed and mustard is generally the first 30–40 days after sowing (DAS). If weeds are controlled during this period, the crop can establish properly and achieve better yield.

Common Weeds in Rapeseed and Mustard Fields

Different types of weeds occur depending on climate, soil condition, and management practices.

Grassy weeds

- *Phalaris minor*
- *Avena fatua* (Wild oat)

Broadleaf weeds

- *Chenopodium album* (Bathua)
- *Anagallis arvensis*
- *Melilotus indica*

Sedges

- *Cyperus rotundus*

These weeds compete aggressively and may reduce nutrient availability and crop growth.

Weed Management Practices

1. Preventive Measures

Preventive practices reduce weed occurrence before crop establishment. Farmers should use clean and certified seed, avoid introducing weed seeds through irrigation water or farm equipment, and remove weeds before they produce seeds.

2. Cultural Methods

Good agronomic practices help suppress weed growth. Timely sowing, maintaining optimum plant population, following crop rotation, and using healthy seed improve crop competitiveness against weeds.

3. Mechanical and Manual Control

Hand weeding is one of the effective methods, especially during early crop growth. One hand weeding at **20–25 DAS** is commonly recommended. Intercultivation between rows can also reduce weed population.

4. Chemical Weed Control

Herbicides can provide effective weed management when applied at the correct time and dose.

- **Fluchloralin (0.75–1.0 kg a.i./ha)** – applied as pre-plant incorporation.
- **Pendimethalin (0.75–1.0 kg a.i./ha)** – applied as pre-emergence within 1–2 days after sowing.
- **Quizalofop-ethyl (50–75 g a.i./ha)** – used post-emergence mainly for grassy weeds.

5. Integrated Weed Management (IWM)

Integrated Weed Management combines preventive, cultural, mechanical, and chemical methods. A practical approach includes timely sowing, pre-emergence herbicide application, and one hand weeding at **25–30 DAS** for better weed suppression.

Conclusion

Effective weed management in rapeseed and mustard is essential for achieving higher productivity and better crop quality. Since weeds compete heavily during the early growth period, adopting preventive, cultural, mechanical, and chemical control measures in an integrated manner can significantly improve crop performance and yield. Sustainable weed management not only increases production but also supports profitable farming.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine
Volume 04, Special Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-17

SUSTAINABLE PLANT HEALTH MANAGEMENT AND ECO-FRIENDLY CROP PROTECTION IN OILSEED-BASED FARMING SYSTEMS

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Introduction

By the beginning of the early 1980s, nations with rapidly growing populations (like India) faced critical deficits in edible oil production within the country. The green revolution successfully saved millions from famine by massively boosting food production, but the intensive farming methods required took a severe toll on soil health. Especially in India, crops like wheat and rice were the principal focus of the revolution. While it mitigated the food deficit, it also brought environmental degradation, socioeconomic disparities, and agricultural vulnerabilities. As a result, oilseed-based farming systems emerged as a critical strategy to achieve self-sufficiency in edible oil production, improving soil health, enhancing rural income, and promoting climate-resilient agriculture.

Although the importance of oilseed cultivation is well established, these crops remain vulnerable to pests, pathogens, and weeds. Climate changes have amplified these challenges (through rising temperatures, erratic rainfall, and shifting pest dynamics), leading to new outbreaks and greater uncertainty of produce. In addition to this, conventional or chemical-based crop protection methods may provide a short-term solution but in the long run led to multiple problems like pesticide resistance, weed shift, environmental degradation, and health hazards.

Sustainable plant health management paves the way to address these concerns. By integrating biocontrol agents, cultural practices, bioformulations, and bio stimulants (like *Neemastra*), farmers can maintain productivity without degrading the environment. This article examines the emerging biotic threats and climate-related challenges affecting oilseed-based farming systems, particularly in fragile tribal and hilly agroecosystems. It highlights sustainable and eco-friendly plant health management approaches, including the five key dimensions of integrated management, along with the role of surveillance, forecasting, and decision-support systems in enhancing crop resilience and productivity.

Oilseed-Based Farming Systems at a glance

Oilseed-based farming systems are agricultural models centred around cultivating oilseed crops like soybeans, groundnuts, mustards, sunflowers, and sesame. Designed to maximise land productivity as they integrate oilseeds with cereals, legumes, and livestock.

These systems provide edible oils, high-protein meals for livestock and improved soil fertility. Common cropping patterns often include intercropping (e.g. 4:2 soybean-pigeon pea system), Sequential cropping like Rice-groundnut (Figure 1), and relay cropping (*e.g.* Rice-Toria/Mustard).

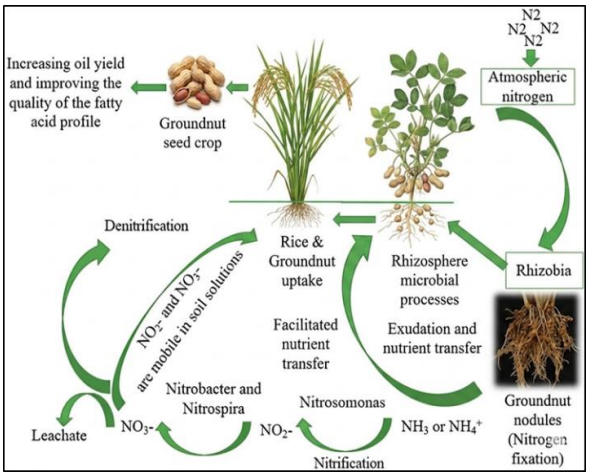


Figure 1. Groundnut and Rice sequential cropping system and it's benefits.

The Biotic Threats and Climatic Interactions in Oilseed-Based Farming Systems

The terms 'tribal' and 'hilly agroecosystem' encompass various ecologically adapted, traditional forest-based farming systems practised by indigenous communities in elevated terrains. The constraints brought up by such an ecosystem vary from region to region. For example, in the case of the Koraput region of Odisha, the fragile and red lateritic soils are more prone to erosion. Similarly, in the case of the northeastern region of India, the agroecosystem is highly affected by soil acidity (over 81% of the region's geographical area is occupied by acid soils, and nearly 65% suffer from strong acidity with a pH below 5.5. Similarly, these regions adopt their own cultural practices, like rainfed cultivation in Koraput, while having terrace and shifting systems for the northeastern regions.

These regions are often affected by various pests, like Bihar Hairy Caterpillar (*Spilosoma obliqua*), Painted Bug (*Bagrada hilaris*)**,** *and* Mustard Sawfly (*Athalia lugens proxima);* secondary pests, species once considered minor, are becoming major threats. Mustard aphids (*Lipaphis erysimi*) now multiply rapidly due to extended mild winters, while stem fly (*Melanagromyza sojae*) in soybeans has expanded into higher altitudes in the northeast. Pod borers (*Helicoverpa armigera*) in sesame and soybean are increasingly destructive as longer growing seasons favour their survival. Diseases like soybean rust (*Phakopsora pachyrhizi)*, *alternaria blight (Alternaria brassicae)*, and white rust *(Albugo candida)* often influence oilseed cultivation as well as the prevalent weeds like *Parthenium hysterophorus, Chenopodium album,* and *Cyperus rotundus,* creating a biological bottleneck.

The effect of climate change on insect pests and diseases of crops is multidimensional. Rising temperature accelerates aphid multiplication in mustard and extends pest survival. Erratic rainfall increases fungal outbreaks (Alternaria in Odisha, rust in NE India). Extended humid Seasons prolong the survival of sucking pests and weeds. Extreme events (flash floods and droughts) weaken crop resilience, making plants more susceptible.

Eco-Friendly and Sustainable Plant Health Management Strategies

Ideal plant health management aims to optimise plant growth and yield while minimising environmental stressors, pests, and diseases. Eco-friendly and sustainable plant health management involves crop diversification, green manuring, seed treatment with bioagents, using botanical extracts, and organic amendments.

The Five Dimensions of Eco-Friendly and Sustainable Plant Health Management Strategies

- **Bio-Intensive Seed Priming:** Tribal farmers rely heavily on farm-saved seeds, which are highly vulnerable to seed-borne pathogens. Coating seeds with bio-agents like *Trichoderma harzianum* or utilising high-altitude thermal solarisation eliminates dormant fungal spores. This ensures strong,

disease-resistant seedling establishment right from the start.

- **Rhizosphere Engineering:** Hilly soils are frequently acidic, which chemically locks away vital nutrients. Inoculating fields with Vesicular-Arbuscular Mycorrhizae (VAM) and Phosphate-Solubilising Bacteria (PSB) extends root networks. This microbial combination fixes phosphorus and accesses deep subsoil moisture, helping oilseeds survive erratic dry spells.
- **Structural Crop Diversification:** Monoculture accelerates pest outbreaks, but structural diversification disrupts these cycles. Row-ratio intercropping (such as mustard with chickpea in a 4:2 setup) breaks host-specific pest cycles. Concurrently, planting yellow marigolds as perimeter trap crops intercepts aphids before they can damage the primary oilseed crop.
- **Botanical Bio-Concoctions:** Where synthetic inputs are unavailable, botanical extracts provide safe, localised pest control. Regular sprays of Neem Seed Kernel Extract (NSKE) and fermented cow urine mixtures (*Jeevamrita*) effectively repel sucking pests. Pairing these with field-level yellow sticky traps controls pest populations without harming native pollinators.
- **Soil-Water Conservation Armour:** Hilly terrains lose topsoil and organic carbon rapidly due to erosion. Sowing oilseeds across contours alongside Soil-binding cover crops drastically slow water runoff. Adding minimal tillage and forest-litter mulching retains critical moisture, regulates soil temperature, and feeds beneficial microbes.

Eco-Friendly Crop Health Management with Natural Predators and Biotic Agents.

In fragile tribal and hilly ecosystems such as Koraput in Odisha and the North Eastern Zone of India, natural predators and bio-agents provide eco-friendly protection for oilseed crops. Lady bugs and lacewings are effective against aphids while predatory mites for whiteflies in mustard and sesame (Figure 2), while hoverflies add both pest control and pollination benefits. Predatory mites and spiders act as generalist hunters in soybean and groundnut fields, reducing caterpillar and jassid populations. Parasitoids like *Trichogramma* target pod borer eggs, and *Aphidius* wasps suppress aphid outbreaks. These bio-agents thrive in diversified, low-input tribal farming systems, offering sustainable pest management that reduces pesticide reliance and supports biodiversity.

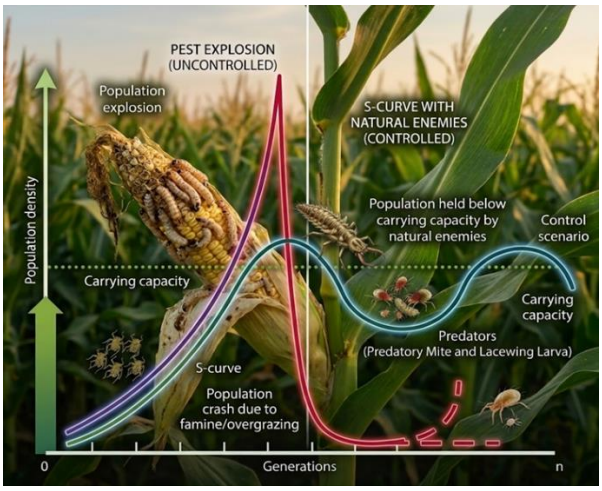


Figure 2. The role of natural enemies in regulation of pest population.

Decision Support Systems for Sustainable Plant Health Management Strategies

In fragile tribal and hilly agroecosystems such as Koraput in Odisha and the North Eastern Zone of India, effective surveillance, forecasting, and decision support systems are essential to manage climate-driven biotic threats in oilseed crops. Community-based monitoring, supported by farmer field schools and simple trap-based surveillance tools like pheromone and light traps, enables early detection of aphids, pod borers, and fungal pathogens. Remote sensing and drone

imagery further strengthen surveillance by identifying canopy stress and weed patches across difficult terrain. Forecasting models that integrate local weather data such as degree-day calculations for aphids or rainfall-linked predictions for Alternaria blight and soybean rust help anticipate outbreaks before they escalate. These forecasts can be translated into practical decision support systems, including SMS advisories in tribal languages, mobile apps, and dashboards that provide threshold-based recommendations for eco-friendly interventions like deploying bio-agents or adjusting sowing dates. By combining traditional knowledge with modern surveillance and forecasting tools, these systems empower resource-constrained farmers to respond proactively to biotic stresses, reduce pesticide misuse, and build resilience against climate variability in fragile oilseed-based farming systems.

Conclusion

The fragile agroecosystems of tribal and hilly regions often face multiple pests, diseases, and weed-related issues due to their erratic rainfall pattern and climate change. Although the conventional management systems can act as a solution for it in the short term, in the long run, it's detrimental to the environment. Eco-Friendly and sustainable plant health management strategies are methods that can counter pests, diseases, and weeds at the same time, improving the soil health. It is more effective when combined with good surveillance, forecasting, and decision support systems.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine
Volume 04, Special Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-18

HARNESSING NATURAL FARMING AND INDIGENOUS TECHNICAL KNOWLEDGE FOR CLIMATE-RESILIENT OILSEED PRODUCTION

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Introduction

In the undulating tribal landscapes, oilseeds are far more than just a commodity crop. For tribal communities often grappling with malnutrition and limited access to diverse food baskets, locally produced oils are a lifeline. Apart from human consumption, some protein-rich oilseed cakes are a vital feed source for backyard poultry and livestock. Their lower input requirement, natural hardiness against climatic shocks and multiple uses makes them a true "famine-proof" asset. Some oils also serve as traditional medicines for certain ailments. India is one of the largest producers in the world, accounting for an estimated production of 40.99 million tons of nine cultivated oilseeds during the year 2025-26 as per Second Advance Estimates released by the Ministry of Agriculture on 10.03.2026. India contributes about 5-6% of the world oilseed production. However, the situation is different in tribal hilly areas where people struggle to raise these crops due to steep slopes, thin top soil, high erosivity, unaffordability of fertilizers, hybrid seeds. Erratic monsoons and prolonged dry spells are the new normal. Thus, there is the need for development of sustainable and low-cost oilseed production system with the integration of Indigenous Technical Knowledge.

2. Natural Farming in Oilseed Cultivation

2.1. Concept of Natural Farming

Natural Farming is a local low-input climate-resilient farming system that advocates no use of synthetic chemical inputs. It emphasizes the enhancements of soil conditions through improved organic matter and biological activity with livestock integration and crop diversification without or minimal disturbance in the physical properties of soil.

2.2. Mixed and Companion Cropping

Tribal oilseed farming systems in Kalahandi (Odisha) and Dangs (Gujarat) follow diversified mixed cropping instead of monoculture. Farmers grow niger with finger millet, sesame and groundnut with pigeon pea, and castor on field bunds. Finger millet protects soil from erosion, pigeon pea fixes atmospheric nitrogen (Fig. 1), and castor improves moisture use through deep roots while its leaves provide natural mulch. These systems enhance soil fertility, conserve resources, suppress weeds, and preserve indigenous landraces. Research by MSSRF (M. S. Swaminathan Research Foundation) in the Koraput-Bastar region identifies them as living gene banks adapted to climatic stresses.

2.3. The Penda or Bewar System (Refined Shifting Cultivation)

Traditional rotational fallow systems like Podu and Jhum are sustainable resource management practices. After cropping, long fallow periods of 15–20 years restore soil organic carbon, improve soil structure, reduce pests and diseases, and ash provides essential nutrients like potash for oilseed cultivation.

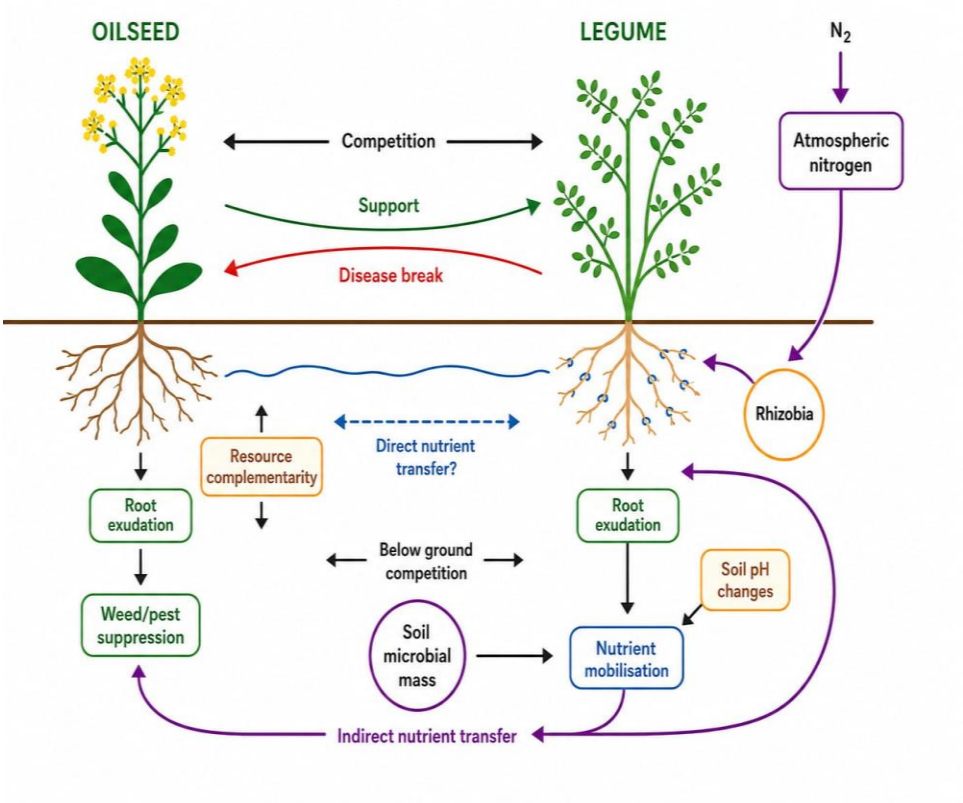


Fig. 1 Legume-Oilseed interactions, Nitrogen cycling and Nutrient pathways

2.4. Home Gardens and Boundary Plantings

Castor, a non-edible but crucial oilseed for lighting and medicinal purposes, is rarely grown in fields. It is grown as a live fence or in backyard gardens, often irrigated with household greywater. This zero-waste, low-effort system ensures a year-round supply of a multi-purpose oilseed without competing for arable land.

2.5. Use of Bio-inputs

Jeevamrit, Beejamrit, and Neemastra are natural bio-inputs used in oilseed cultivation. Jeevamrit improves soil microbial activity and nutrient availability, Beejamrit protects seeds and enhances germination, while Neemastra controls pests naturally. Together, they reduce chemical dependency and promote sustainable crop production.

3. Indigenous Technical Knowledge (ITK) in Oilseed Farming

What is often dismissed as tradition is, in fact, a long-term, field-verified scientific trial. Tribal Indigenous Technical Knowledge is not a random collection of rituals; it is a coherent system of natural resource management fine-tuned to the fragility of hilly agro-ecosystems.

3.1. Soil and Moisture Conservation:

The most visible ITK is terrace farming, but the invisible wisdom lies beneath.

- Stone Bunds and Vegetative Barriers: Tribes construct small stone bunds along the contour and cultivate indigenous grasses like vetiver alongside. These structures significantly reduce runoff velocity, allowing water to infiltrate and minimizing soil erosion.

- Perception-Based Cropping: Farmers use palpable, local indicators to decide sowing. An ITK from the region is, "When the Palash (*Butea monosperma*) tree is in full bloom, it is time to sow niger," which coincides with optimal soil temperature and moisture availability. This indigenous phenology is a precise climate-sensing tool.
- In-situ Composting and Bio-mulching: The "Bun" or "Badi" system of the Baiga and Gond tribes focuses on creating raised mounds of forest leaf litter for planting oilseeds like sesame or castor. The decomposing biomass becomes a "rhizosphere hotspot," teeming with mycorrhizal fungi that act as a secondary root system for the plant, scavenging phosphorus from the nutrient-poor hill soils and delivering water with remarkable efficiency. The heap acts as a water-holding sponge.

3.2. Nutrient and Pest Management:

- Farmyard Manure and Forest Litter: With little access to chemical fertilizers, soil fertility is maintained by incorporating well-decomposed farmyard manure and, critically, leaf litter collected from the surrounding forests. The application of Sal (*Shorea robusta*) or Neem leaves to fields is an ITK that serves dual purposes: it adds organic matter and acts as a soil-borne pest and disease suppressant.
- Botanicals and Ash for Pest Control: Stored oilseeds are protected by mixing them with dry neem leaves, wood ash, or fine sand-an inert dust technology known to tribal communities for generations (Fig. 2). To protect against sucking pests in the field, a fermented slurry of local botanicals (like Datura or Calotropis leaves) and cow urine is sprayed, a potent homemade insect repellent.

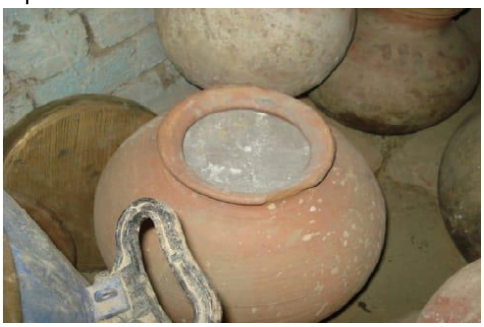


Fig. 2 Using wood ash for storing of seeds

4. Challenges

- Lack of scientific validation: Many indigenous practices are based on generations of farmer experience but lack systematic scientific evaluation and evidence-based validation before large-scale adoption.
- Poor documentation and risk of knowledge loss: A large amount of traditional agricultural knowledge exists orally among farming communities and is gradually disappearing due to changing agricultural practices and reduced transmission between generations.
- Difficulty in adapting ITK to modern farming systems: Traditional practices are often location-specific and may require modification before being applied under different agro-climatic conditions or modern production systems.
- Limited awareness among farmers and policymakers: Many farmers and decision-makers are not fully aware of the potential benefits of combining traditional knowledge with scientific technologies.

5. Opportunities

The goal is not to replace these landraces with improved hybrids, but to use them as the foundation.

- The process of Participatory Varietal Selection (PVS) formalizes this ancient wisdom. Instead of delivering finished varieties to farmers, scientists and farmers collaborate. Breeding lines and local landraces are grown together in the farmer's field, under their real-world conditions of low fertility and uncertain water. The farmers evaluate them using their own criteria: not just yield, but taste of the oil, grain filling under stress, and compatibility with their intercropping systems. This leads to the identification of varieties that are genuinely adapted and acceptable.
- Biotechnological interventions, like Marker-Assisted Selection (MAS), can then accelerate this process. A gene for water-use efficiency identified in a local landrace through collaborative research with a State Agricultural University (SAU) can be flagged, and progeny carrying that gene can be fast-tracked back into the farmer's field. The lab becomes a service provider to the gene pool that the farmer has conserved.

6. Success Stories and Case Studies

- A local sesame landrace from the tribal belt of Rajasthan and Gujarat, sometimes referred to by names like "Gujarat Til-2" or simply Desi Til. This landrace, selected by farmers over countless generations, exhibits exceptional thermotolerance. It can withstand the scorching pre-monsoon heat and still set viable seed. This is genetic improvement achieved not by a breeder with a crossing block, but by a farmer with a keen eye, saving seed from the best-performing plant in the toughest year.
- The Bundelkhand region of Uttar Pradesh possesses rich Indigenous Technical Knowledge (ITK) developed by farmers for natural resource management, crop protection, climate adaptation, and sustainable farming. However, modern agriculture has increased dependence on chemical inputs and high-yielding varieties (HYVs), leading to the decline of traditional practices. Integrating ITKs with scientific approaches has shown significant benefits. Crop residue management and soil mulching can reduce cultivation costs by Rs. 2500–3000/ha, save 20% water, and increase yield by 20%. Watershed-based interventions improve water availability by 3–4 months during summer, while Integrated Nutrient Management reduces fertilizer use by 25%. Agroforestry systems enhance productivity by nearly 120%, highlighting the importance of combining indigenous wisdom with modern technologies for climate-resilient agriculture.
- A field experiment conducted at the Department of Vegetable Crops, Tamil Nadu Agricultural University, Coimbatore, evaluated the performance of cabbage (*Brassica oleracea* var. *capitata* L.) under organic, conventional, and natural farming systems. The results demonstrated the superiority of the organic production system in terms of growth, yield, and quality attributes. Organic farming recorded the highest plant height (21.47 cm), stalk length (8.49 cm), dry matter accumulation (71.34 g plant^{-1}), head diameter (17.70 cm), head

compactness (33.91), and head weight (945.35 g plant^{-1}). Consequently, the highest cabbage yield of 24.92 t ha^{-1} was achieved under the organic system, outperforming both conventional and natural farming practices. Quality parameters were also significantly improved, with higher total soluble solids (6.54 °Brix), longer shelf life (12.21 days), and greater ascorbic acid content (44.26 mg 100 g^{-1}).

7. Conclusion

The challenge today is that these systems are fragile. They are undocumented, often dismissed as unproductive, and are eroding under the pressure of market-driven monocultures. Writing about them is the first step in protecting them. Climate-smart agriculture for hilly ecosystems cannot be a top-down technology transfer. It must be a respectful dialogue with the indigenous knowledge holders. The tribal farmer who chooses a specific local niger landrace because its flower attracts a beneficial predator wasp is an agroecologist in their own right. As we celebrate modern science and biotechnology, we must also learn to listen to the whispers from the hills. In the natural oilseed production systems of India's tribes, we don't just find survival mechanisms; we find the principles of permanence.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine
Volume 04, Special Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-19

WEED MANAGEMENT IN RAPESEED AND MUSTARD: AGRONOMIC REALITIES, INNOVATIONS, AND POLICY PATHWAYS

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Introduction

Rapeseed-Mustard is the third important oilseed crop in the world after soybean (*Glycine max*) and palm oil (*Elaeis guineensis jacq*.). But in India second major oilseed crop after groundnut, accounting nearly 25-30% of total oilseeds production. Mustard is primarily cultivated in rainfed, resource-constrained regions across the Indo-Gangetic plains, with Rajasthan, Haryana, Uttar Pradesh, and Madhya Pradesh.

Securing self-sufficiency in edible oils is one of the most pressing macroeconomic and strategic challenges facing Indian agriculture today. India currently relies heavily on foreign imports to meet its domestic oil requirements. This structural deficit results in an annual import bill that has surged to approximately ₹1.6 lakh crore, draining valuable foreign exchange reserves. To correct this imbalance, agricultural policy must focus on maximizing the productivity of the Rabi season's primary oilseeds: rapeseed and mustard (*Brassica spp.*). Together, these crops account for nearly 29% of the nation's domestic oil production, making them important to stabilizing our agricultural economy.

While public policy frequently emphasizes macro-level inputs such as, high-yielding variety seed distribution, micro-irrigation projects, and Minimum Support Price (MSP) adjustments. However, the productivity of rapeseed and mustard facing weed infestation, a significant threat that quietly limits these advancements. For micro, small and medium farmers in these arid and semi-arid zones, reducing yield due to weeds directly reduces profit margins, stalling rural economic growth. Weeds such as Invasive plants, opportunistic broad-leaved weeds, and destructive root parasites like *Orobanche* are regarded as one of the major negative factors of crop production loss due to competition for nutrients, moisture, light, and space which has been reported as high as 30-70%. Because *Brassica* species grow slowly during their early vegetative phase, they are highly vulnerable to weed competition during the initial 40 days after sowing. There are several methods available to manage weeds effectively and efficiently in the field.

As India balances the ecological risks of chemical runoff against a shrinking rural labour supply, weed management is no longer just a routine farm chore. It has become a complex policy priority where agronomic science, environmental safety, and biotechnological innovations intersect.

The critical period of crop-weed competition

The critical period of crop-weed competition is the specific window during the crop lifecycle when weed growth causes irreversible yield losses. For rapeseed and mustard, this critical window occurs between 15 and 40 days after sowing (DAS). During the first fortnight, both the crop and the weeds emerge simultaneously, drawing minimally from the soil's

nutrient reserves. However, once the plants enter the active vegetative stage, their demand for resources increases sharply. If weeds are left unchecked during this 25-day window, they outgrow the young mustard seedlings, shading them out and depleting soil moisture. Agronomic trials show that keeping fields weed-free during this timeframe preserves the crop's full genetic yield potential. Conversely, failing to manage weeds during this period can reduce final yields by 15% to 45%.

Major weed flora in *Brassica* agro-ecosystems

Effective management requires precisely identifying the target weed profile. The dominant weeds affecting Indian mustard fields are listed here.

Weed Species	**Common Name**	**Damage Mechanism & Characteristics**
Orobanche aegyptiaca	Broomrape	Total root parasite; lacks chlorophyll; attaches directly to mustard roots to get moisture and nutrients; causes severe stunting or total crop death.
Chenopodium album *Melilotus indica*	Bathua Senji	Fast-growing annual with wide leaves; create a dense canopy that blocks sunlight from young mustard plants.
Asphodelus tenuifolius	Piazi	Perennial and annual monocot with fibrous root network; highly depleting basal fertilizers and shallow soil moisture.
Cynodon dactylon	Doob grass	

Integrated Weed Management (IWM)

Relying on a single control method such as, hand weeding or chemical sprays often leads to management failures or weed resistance. Integrated Weed Management (IWM) in rapeseed and mustard combines cultural, mechanical, and chemical practices. Because mustard is highly susceptible to weed competition during early growth stages (15-40 days after sowing), a multi-tactic approach ensures optimal seed yield and crop quality.

Why Integrated Weed Management (IWM)?

Integrated Weed Management (IWM) is essential for effective and sustainable weed control due to several key reasons:

1. Variable conditions: A single weed control method might be effective in one situation but not in another due to differences in environmental conditions, soil types, crop systems, and weed species present. IWM allows for tailored strategies that adapt to specific contexts, improving overall effectiveness.

2. Limited herbicide efficacy: No single herbicide can effectively control all weed species. Different weeds respond variably to herbicides, and IWM incorporates various methods to address this diversity, ensuring a broader spectrum of control.

3. Herbicide-resistance: Continuous use of the same herbicide can lead to the development of resistance in weed populations. IWM mitigates this risk by rotating herbicides with different modes of action and integrating non-chemical methods, which helps maintain herbicide effectiveness.

4. Monocropping: Relying solely on one weed management practice can result in negative consequences, such as the proliferation of specific weed species. For example, in rice and wheat cropping systems, continuous herbicide application can lead to the dominance of resistant species like *Phalaris minor*. IWM promotes diverse strategies that help manage such risks.

5. Weed population dynamics: Using only one method of control can lead to an increase in specific weed populations. IWM employs a combination of cultural, mechanical, biological, and chemical strategies to manage and suppress weed populations more effectively.

6. Environmental and health concerns: The over-reliance on herbicides can have detrimental effects on the environment, including soil degradation, water contamination, and harm to non-target species, as well as potential risks to human health. IWM emphasizes integrated strategies that reduce herbicide dependency, thereby minimizing environmental impact and promoting safer agricultural practices.

7. Sustainable agricultural practices: IWM fosters sustainable farming systems that maintain ecological balance, enhance biodiversity, and preserve soil health. By integrating multiple weed control methods, IWM supports the long-term productivity of agricultural lands.

8. Cost-effectiveness: While IWM may require a higher initial investment in terms of knowledge and management, it often results in cost savings over time by reducing herbicide use, preventing weed resistance, and improving crop yields.

9. Adaptability to change: IWM is dynamic and allows farmers to adapt their strategies in response to emerging weed threats, climate change, and shifting agricultural practices, making it a robust approach for modern agriculture.

I. Cultural & mechanical methods

a) **Stale seedbed method:** Apply a pre-sowing irrigation 10 to 12 days before sowing to encourage latent weed seeds in the topsoil to germinate. Follow with shallow tillage or a non-selective herbicide like glyphosate (1.0 kg/ha) to clear this initial weed flush, establishing a clean field under conservation or zero-tillage systems.

b) **Planting timing:** Timely planting can enable crops to establish before weeds emerge, minimizing competition during critical growth periods. Sow the seeds during the optimal agronomic window (from the last week of October to the first half of November). Use competitive, rapid-growing varieties planted at a uniform 30 cm row spacing. This promotes quick canopy closure, naturally shading out light-sensitive weed seedlings.

c) **Crop rotation:** Rotating mustard with cereals helps break the life cycle of problematic weeds.

d) **Intercropping**: Growing different crops in close proximity can enhance competition for light, nutrients, and space, effectively suppressing weeds.

e) **Cover crops**: Planting cover crops during the off-season can suppress weeds by competing for resources, preventing soil erosion, and improving soil health.

f) **Mulching:** Applying crop residues or organic mulches right after sowing physically suppresses early weed emergence and conserves soil moisture. Mulching has a smothering effect on weeds by restricting solar light which affects photosynthesis by weeds. It is effective against annual weeds and some

perennial weeds. Mulching with straw when applied on soil surface does not allow weeds to germinate as light does not reach the soil. Mulches not only conserve soil moisture but also impart beneficial effects like suppression of extreme fluctuation of soil temperature, reduce water loss through evaporation resulting in more stored soil moisture.

II. Mechanical and physical control

a) **Hand weeding:** Perform one hand-weeding or mechanical wheel-hoeing within the critical 20-30 days after sowing. This removes any weeds that escaped the pre-emergence treatment and breaks up the soil crust, improving aeration and nutrient uptake for the young mustard crop.

b) **Polyethylene mulch:** Covering the soil with clear plastic for several weeks can trap heat and kill weed seeds and seedlings through high temperatures

III. Chemical method

Apply Pendimethalin at 0.75 kg a.i./ha or Oxadiargyl at 90 g/ha dissolved in 500 liters of water per hectare using a flat-fan nozzle. This creates a thin chemical layer on the soil surface that controls emerging annual grasses and broad-leaved weeds before they break through.

Biological & parasitic weed control (Orobanche)

- *Orobanche* (broomrape) is a notorious parasitic weed for mustard.
- Control requires manual uprooting before it sets seeds, intercropping with non-host crops (like chickpea or lentil), and soil solarization prior to sowing to reduce the seed bank in the soil.

Historical milestones in indian weed research

The systematic approach to managing crop competition in India has transitioned through distinct policy era:

- **Inception of ICAR coordinated research (1952)**

The Indian Council of Agricultural Research (ICAR) initiated early systematic weed control studies, focusing on basic cultural practices and manual removal methods for staple grains.

- **The chemical shift & green revolution (1970s - 1980s)**

Introduction of dinitroaniline herbicides like, fluchloralin and pendimethalin. These provided a reliable pre-emergence chemical shield, reducing early-stage labour demands for oilseeds and pulses.

- **Rise of integrated weed management (IWM) (2000s)**

Agronomists shifted away from a pure chemical focus toward IWM systems. Research combined conservation agriculture (zero tillage, organic mulching) with targeted chemical applications to preserve soil biology.

- **The biotech & mutation breeding era (2022-2026)**

Marked by legal reviews of transgenic HT crops (such as DMH-11) and the successful field introduction of non-GM, IMI-resistant mustard varieties developed through targeted enzyme mutations.

Context in recent news & strategic importance

The scientific and policy conversation around oilseed production has changed significantly due to two major developments:

- **The commercialization of non-GM IMI-resistant hybrids:** National research institutions and private partners successfully commercialized Imidazolinone-

Resistant (IMI-resistant) mustard hybrids. Developed through target-site mutation breeding rather than transgenic insertion, these varieties tolerate specific post-emergence broad-spectrum herbicides. This offers a clear regulatory pathway that avoids the biosafety gridlocks associated with transgenic crops like GM Mustard (DMH-11).

- **Edible oil import volatility:** Geopolitical shifts and supply chain disruptions have highlighted the vulnerability of importing vital food commodities. Enhancing the per-hectare yield of domestic mustard through targeted weed control is now recognized as an essential strategy for national food security.

Advantages of modern interventions

- **Mitigating rural labour scarcity:** Peak weeding periods often overlap with acute seasonal labour shortages, driving up manual production costs. Pre- and post-emergence herbicides offer a cost-effective alternative that keeps farming viable for smallholders.
- **Managing subterranean parasites:** Traditional mechanical hoeing cannot resolve root parasites like *Orobanche*, because manual tools cannot detach the parasite from the host root system below ground. Herbicide-tolerant innovations allow farmers to apply systemic chemicals that eliminate *Orobanche* without harming the mustard plant.
- **Maximizing input efficiency:** Removing early weed competition ensures that applied nitrogen, phosphorus, and irrigation water are fully utilized by the cash crop, maximizing seed oil content.

Risks and structural challenges

- **Herbicide-resistance and selection pressure:** Overusing a single chemical molecule (such as relying exclusively on pendimethalin) accelerates selection pressure. This can lead to the emergence of herbicide-resistant weed biotypes.
- **Soil microflora disruptions:** Indiscriminate chemical applications can damage beneficial soil microbes, alter earthworm activity, and leave persistent residues that affect subsequent crops in the rotation, such as mungbean or direct-seeded rice.
- **The transgenic regulatory debate:** The deployment of Herbicide-Tolerant Genetically Modified (HT-GM) crops remains a subject of legal and environmental discussion regarding gene flow, potential "superweeds," and seed corporate governance. This highlights the practical value of non-GM mutation breeding solutions.

Conclusion

Addressing weed-induced yield losses in rapeseed and mustard is essential for achieving long-term self-reliance (*Atmanirbharata*) in India's edible oil sector. Relying on a single approach, whether it is cost-prohibitive manual labour or continuous chemical applications, is no longer sustainable.

The path forward requires a coordinated transition toward localized Integrated Weed Management (IWM) frameworks. This approach combines traditional conservation practices, like stale seedbeds and precise crop spacing, with modern seed technologies like non-GM mutation-bred varieties.

To drive this shift, the Ministry of Agriculture, state agricultural universities, and extension networks must focus on clear priorities:

1. Expand educational programs to train farmers in proper herbicide rotation, protecting soil microbial health and delaying chemical resistance.
2. Support small-scale manufacturing of mechanical weeding tools to help farmers manage labour shortages.
3. Accelerate research into biological control agents that target parasitic weeds like *Orobanche* naturally.

By protecting India's golden mustard fields from weed competition, we can improve smallholder farm incomes, protect fragile soil ecosystems, and structurally reduce the nation's reliance on foreign edible oil imports.

GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine

Volume 04, Special Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-20

BIOTIC STRESS CHALLENGES IN THE ERA OF CLIMATE CHANGE: IMPLICATIONS FOR FOOD SECURITY AND AGRICULTURAL RESILIENCE

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Abstract

Climate change is fundamentally reshaping the dynamics of biotic stresses in agricultural and natural ecosystems worldwide. The interplay between rising temperatures, altered precipitation patterns, and extreme climate events such as El Nino - Southern Oscillation (ENSO) is accelerating the emergence, spread, and virulence of pests, pathogens, and invasive species. This review synthesises current knowledge on surveillance technologies, predictive modelling frameworks, and integrated management strategies for biotic stresses under changing climatic conditions. Special emphasis is placed on the implications of El Nino events for Indian agriculture, where drought, heat stress, and disrupted monsoons exacerbate crop losses due to insects, fungi, bacteria, and weeds. Remote sensing, genomic surveillance, AI-driven early-warning systems, and climate-smart pest management are discussed as pillars of an adaptive response framework. The paper underscores the urgent need for multidisciplinary, data-driven approaches to safeguard food security in a warming world.

Keywords: biotic stress, climate change, El Nino, ENSO, pest surveillance, disease forecasting, integrated pest management, India, food security

1. Introduction

Global food security faces a dual threat from the accelerating pace of climate change and the concurrent rise in biotic stresses pests, pathogens, weeds, and invasive organisms that devastate crops, forests, and ecosystems.

The Intergovernmental Panel on Climate Change (IPCC, 2022) has documented that warming trends, shifting precipitation regimes, and increasing frequency of extreme weather events are fundamentally altering host–pathogen–environment interactions, creating novel and unpredictable disease and pest outbreaks (Bebber *et al.*, 2013).

Biotic stresses cause an estimated 20–40% of global crop losses annually, costing the world economy over USD 220 billion (Savary *et al.*, 2019). Under climate change, these losses are projected to intensify as pest ranges expand poleward and to higher elevations, overwintering survival improves, and phenological mismatches arise between pests and their natural enemies (Deutsch *et al.*, 2018). Meanwhile, pathogens evolve faster under heat stress, and droughts predispose plants to opportunistic infections.

Among climate drivers, the El Nino–Southern Oscillation (ENSO) is one of the most powerful modulators of interannual climate variability globally. In India, El Nino events consistently suppress the South Asian monsoon,

leading to drought, heatwaves, and increased irrigation demand.

These conditions drastically alter the epidemiology of crop diseases and pest population dynamics, threatening the livelihoods of over 600 million farmers (Kumar *et al*., 2020).

Effective surveillance, forecasting, and management of biotic stresses under climate change require integrated frameworks that combine remote sensing, genomic tools, machine learning, and climate modelling with traditional agronomic practices. This review critically examines these frameworks, with a focus on El Nino impacts on Indian agriculture, and charts a roadmap toward climate-resilient biotic stress management.

2. Climate Change and the Dynamics of Biotic Stresses

2.1 Temperature and Pathogen Virulence: Rising temperatures directly influence the physiology, reproduction, and geographic distribution of plant pathogens and pests. Fungal pathogens such as Magnaporthe oryzae (rice blast) and Fusarium species exhibit accelerated sporulation and infection cycles at elevated temperatures, resulting in more frequent disease epidemics (Luck *et al*., 2011). For insect pests, a 2°C rise in mean temperature can shorten generation time by 10–25%, exponentially increasing population growth rates (Deutsch *et al*., 2018). The northward migration of the fall armyworm (Spodoptera frugiperda) into previously unaffected regions of South Asia exemplifies how warming enables range expansion of invasive pests (Early *et al*., 2018).

2.2 Altered Precipitation and Disease Epidemics: Precipitation patterns directly regulate moisture conditions required for fungal sporulation, bacterial multiplication, and soil-borne disease cycles. Extended droughts increase plant susceptibility by inducing osmotic stress and weakening immune signalling pathways, while sporadic intense rainfall events create ideal conditions for waterborne pathogens such as Phytophthora infestans (late blight) (Pautasso *et al*., 2012). Reduced rainfall also concentrates aphid and whitefly populations on stressed plants, amplifying vectored viral diseases such as tomato leaf curl and cassava mosaic virus.

2.3 CO_2 Enrichment and Host–Pathogen Interactions: Elevated atmospheric CO_2 concentrations affect plant physiology in ways that can alter susceptibility to pests and pathogens. While CO_2 fertilisation can boost plant growth and alter canopy microclimate, it often reduces nitrogen concentration in plant tissues, affecting herbivore nutrition and driving compensatory feeding. Additionally, elevated CO_2 can suppress plant defence gene expression (Zavala *et al*., 2013), making crops more vulnerable to chewing insects and necrotrophic pathogens. These physiological changes complicate disease and pest management in future high-CO_2 scenarios.

3. El Nino and Biotic Stress in India

3.1 El Nino–Southern Oscillation: Overview:

El Nino refers to the periodic warming of sea surface temperatures (SSTs) in the central and eastern tropical Pacific Ocean, occurring every 2–7 years as part of ENSO. During El Nino years, the Walker Circulation weakens, causing suppressed convection over the Indian Ocean and a deficient Indian Summer Monsoon (ISM). The India Meteorological Department (IMD) has documented that nearly 60% of El Nino years since 1950 have been associated with below-normal monsoon rainfall in India (Rajeevan *et al*., 2012). The 2015–16 El Nino, one of the strongest on record, caused severe drought across 11 Indian states, devastating kharif crop production and triggering acute food and fodder shortages (Government of India, 2016).

3.2 El Nino, Drought, and Pest Dynamics:

El Nino-driven droughts in India significantly reshape pest and disease dynamics. Moisture deficit during kharif (June–September) reduces the natural suppression of sucking pests—thrips, mites, aphids, and whiteflies proliferate on drought-stressed crops with compromised physical and biochemical defences. During the 2009 and 2015 El Nino events, locust invasions (Schistocerca gregaria) intensified in Rajasthan and Gujarat due to dry conditions facilitating breeding and migration from desert ecosystems (CIB&RC, 2020).

Paradoxically, droughts followed by unseasonal rains—a pattern often observed in El Nino years—create episodic humidity spikes that trigger explosive outbreaks of airborne fungal diseases. Rice false smut (Ustilaginoidea virens), sheath blight (Rhizoctonia solani), and brown spot (Bipolaris oryzae) have shown marked increases in prevalence during post-El Nino La Nina rebounds in eastern India (Sinha *et al*., 2018). Wheat rust (Puccinia striiformis and P. triticina) has also demonstrated increased virulence during years with unusual temperature fluctuations associated with ENSO cycles (Singh *et al*., 2016).

3.3 Impacts on Crop Production and Farmer Livelihoods:

The consequences of El Nino-exacerbated biotic stresses on Indian agriculture are severe and multidimensional. During El Nino years, paddy production in drought-prone states—Odisha, Chhattisgarh, Jharkhand, and Maharashtra—declines by 15–30%, with additional losses from pest and disease outbreaks compounding weather-induced stress (Kumar *et al*., 2020). Cotton crops in Maharashtra and Telangana suffer elevated bollworm (Helicoverpa armigera) pressure under dry, warm conditions, contributing to farmer indebtedness and agrarian crisis. The 2014–15 El Nino was associated with a spike in Bt cotton pest resistance reports and increased pesticide expenditure by 20–35% in affected districts (Nagrare *et al*., 2018).

The IMD and ICAR have identified ENSO monitoring as a national priority for crop loss prevention and insurance scheme calibration (IMD, 2019). Integration of seasonal climate forecasts with crop protection advisories has been piloted in Maharashtra and Andhra Pradesh under the National Food Security Mission, showing early promise in reducing pesticide costs while maintaining yields (Rao *et al*., 2021).

3.4 Emerging Pathogens Under El Nino Conditions:

Climate variability associated with El Nino has been linked to the emergence and re-emergence of novel pathogens in India. The 2016 outbreak of a new race of wheat yellow rust (Pst-Warrior) in Punjab and Haryana was temporally correlated with unusual temperature patterns during the 2015–16 El Nino, enabling the survival and dispersal of new pathotypes not previously detected in the region (Singh *et al*., 2016). Similarly, southern corn leaf blight (Cochliobolus heterostrophus) resurgence in peninsular India during drought years reflects the expanding risk profile under ENSO influence. These events underscore the importance of maintaining active pathotype monitoring programs linked to climate forecasting systems.

4. Surveillance Technologies for Biotic Stresses

4.1 Remote Sensing and Satellite-Based Monitoring:

Satellite remote sensing has transformed large-scale surveillance of crop health and pest/disease outbreak detection. Multispectral and hyperspectral sensors aboard platforms such as Sentinel-2, MODIS, and Landsat enable the identification of spectral signatures associated

with pathogen infection, insect defoliation, and weed infestations weeks before visible symptoms appear (Zhang *et al*., 2019). Vegetation indices - NDVI, NDRE, and NDWI - are routinely used to detect early stress hotspots across thousands of hectares simultaneously.

In India, ISRO's National Remote Sensing Centre (NRSC) employs RISAT and Resourcesat satellites for crop health monitoring under the Mahalanobis National Crop Forecast Centre (MNCFC). Early detection of locust swarms using MODIS NDVI anomaly detection provided 48–72-hour advance warning during the 2019–20 invasions in northwest India, saving an estimated 1.5 million hectares from devastation (FAO, 2020).

4.2 Genomic and Metagenomic Surveillance:

Next-generation sequencing (NGS) and metagenomics have revolutionised pathogen surveillance by enabling the identification of novel viruses, fungi, and bacterial strains without prior knowledge of the causal organism. Environmental DNA (eDNA) metabarcoding of soil, air, and water samples can detect pathogen inoculum concentrations below threshold levels, providing early warnings of potential epidemics (Grunwald *et al*., 2016). Real-time portable sequencing devices—such as Oxford Nanopore MinION—are increasingly deployed in field conditions for rapid pathogen identification in India's major agricultural zones. The ICAR has deployed genomic epidemiology protocols for wheat rust surveillance across 14 states through the AICRP on wheat and barley (Prasad *et al*., 2020).

4.3 IoT-Based Field Sensors and Smart Pest Trapping:

The Internet of Things (IoT) is enabling dense, real-time networks of environmental and pest monitoring sensors in agricultural fields. Smart weather stations integrated with automated insect traps (light, pheromone, and suction traps) provide continuous data on pest flight activity correlated with temperature, humidity, and wind patterns. AI-enabled image recognition systems mounted on these traps automatically identify trapped species and transmit counts to cloud-based dashboards (Potamitis *et al*., 2017). Pilot deployments of IoT pest monitoring networks in Punjab and Karnataka under India's Digital Agriculture Mission have demonstrated 40–60% improvement in early warning timeliness for key pests such as brown planthopper and stem borers.

5. Forecasting Frameworks for Climate-Driven Biotic Stresses

5.1 Mechanistic and Process-Based Models:

Process-based epidemiological models simulate pest and disease development as functions of temperature, humidity, host growth stage, and inoculum load. Models such as CROPGRO, EPIPRE (for wheat diseases), and CLIMEX (for pest habitat suitability) have been widely validated for predicting disease onset under variable climate scenarios (Savary *et al*., 2012). Coupled crop–climate models driven by CMIP6 General Circulation Model outputs are used to project future disease pressure under RCP4.5 and RCP8.5 emission pathways, informing long-term breeding and management strategies.

5.2 Machine Learning and AI-Driven Prediction:

Machine learning algorithms—including Random Forests, Support Vector Machines, and deep Convolutional Neural Networks (CNNs)—have demonstrated superior predictive performance for biotic stress forecasting by identifying non-linear relationships across large, heterogeneous datasets (Mohanty *et al*., 2016). Deep learning models trained on millions of disease symptom images have achieved over 95% accuracy in identifying more than 50 crop

diseases using smartphone cameras. Long Short-Term Memory (LSTM) neural networks trained on historical climate and outbreak data provide 4 - 6 week forecasts of aphid and whitefly population peaks correlated with ENSO climate indices (Araya-Alman *et al*., 2020). ICAR-NIASM has developed ENSO-linked seasonal pest forecasting models for major kharif pests, issuing advisory bulletins 8–12 weeks in advance to state agriculture departments (Vennila *et al*., 2022).

5.3 Species Distribution and Risk Mapping:

MaxEnt, BIOCLIM, and ensemble species distribution modelling approaches project future geographic distributions of pest and pathogen species under climate change scenarios. These models have predicted northward expansion of tropical pests such as fall armyworm and tomato pinworm (Tuta absoluta) into South Asian regions within the next two to three decades under RCP8.5 (Early *et al*., 2018). In India, risk maps generated for wheat blast (Magnaporthe triticicola) have guided pre-emptive seed health protocols and border surveillance to prevent introduction of this devastating pathogen already present in Bangladesh (Callaway, 2016).

6. Integrated Management of Biotic Stresses Under Changing Climates

6.1 Climate-Smart Pest Management:

Climate-smart pest management (CSPM) integrates forecasting, biological control, cultural practices, and targeted chemical interventions calibrated to real-time climate conditions and risk levels. The FAO Farmer Field School model adapted for climate-responsive IPM in South Asia has demonstrated 25–40% reductions in pesticide use alongside equivalent or improved yields (FAO, 2016). Key practices include adjusting planting dates to escape peak pest pressure periods predicted from seasonal climate forecasts, deploying climate-tolerant resistant varieties, and implementing push-pull cropping systems that manipulate habitat to disfavour pests while favouring natural enemies.

6.2 Host Resistance and Breeding for Climate Resilience

Developing and deploying pest- and disease-resistant varieties adapted to climate-stressed environments is the most durable and cost-effective management strategy. Speed breeding programs have accelerated the development of wheat varieties with combined resistance to multiple rust races suitable for projected warming conditions in the Indo-Gangetic Plain (Hickey *et al*., 2019). ICAR and CGIAR have developed climate-ready rice varieties combining submergence tolerance (Sub1 gene), drought tolerance (DRO1), and blast resistance (Pi genes) for use in El Nino-vulnerable regions (Ismail *et al*., 2013).

6.3 Biological Control and Microbiome-Based Approaches:

Biological control agents (BCAs) are increasingly recognised as key components of sustainable biotic stress management under climate change. However, their efficacy is itself climate-sensitive; temperature and humidity affect the survival, sporulation, and parasitism rates of beneficial organisms. Research is intensifying on selecting BCA strains tolerant to heat and drought stress (Lacey *et al*., 2015). Endophytic fungi and plant-growth-promoting rhizobacteria (PGPR) that induce systemic resistance (ISR) are being evaluated for their ability to prime plant immunity under drought and heat conditions associated with El Nino seasons.

6.4 Digital and Precision Agriculture Tools:

Precision agriculture tools - including drone-based crop surveillance, variable-rate pesticide application systems, and AI-powered decision-support platforms—are transforming the efficiency and targeting of biotic stress

management. Drones equipped with multispectral sensors can detect disease hotspots at sub-field resolution, enabling targeted spraying that reduces chemical use by 30–50% while maintaining efficacy (Zhang & Kovacs, 2012). Digital platforms such as Plantix, CropIn, and India's AgriStack are aggregating pest and disease reports from millions of farmers, creating near-real-time surveillance maps with epidemiological resolution unprecedented in agriculture.

Challenges and Future Directions

Despite significant technological advances, several critical challenges limit the effectiveness of biotic stress surveillance and management under climate change. Data gaps remain acute in tropical developing regions, where smallholder farming systems predominate and infrastructure for systematic pest monitoring is limited. The integration of climate model outputs—inherently probabilistic—with deterministic pest management decision thresholds requires new interdisciplinary frameworks that account for uncertainty propagation.

Socioeconomic barriers including limited access to digital tools, credit constraints, and low extension service penetration limit technology adoption by the most vulnerable farmers in El Nino-affected regions of India. Governance frameworks for data sharing across national and regional surveillance networks remain fragmented. The accelerating evolution of pesticide resistance and pathogen virulence under climate pressure demands continuous monitoring and dynamic updating of management recommendations.

Future research priorities include:

(1) development of multi-hazard early warning systems that simultaneously forecast climate extremes, pest outbreaks, and yield impacts; (2) integration of ENSO seasonal forecasts into national crop insurance and contingency planning systems; (3) participatory design of climate-smart pest management protocols with farming communities; (4) investment in climate-resilient biological control pipelines; and (5) establishment of open-access, interoperable surveillance data platforms linking national agricultural research systems across South Asia.

Conclusion

The convergence of climate change and escalating biotic stresses poses one of the most complex and urgent challenges to global food security in the 21st century. El Nino events act as powerful stress multipliers in India, simultaneously suppressing the monsoon, creating drought conditions, and triggering outbreaks of pests and pathogens that exact enormous tolls on crop production and farmer welfare. Addressing this challenge requires a paradigm shift from reactive, calendar-based pest management to proactive, climate-informed, data-driven systems.

Advances in remote sensing, genomic surveillance, IoT sensor networks, and machine learning are providing the technological foundations for such systems.

However, their full potential can only be realised through sustained investment in rural digital infrastructure, inclusive extension systems, interdisciplinary research partnerships, and policy frameworks that embed climate intelligence into agricultural decision-making at every level—from the individual farmer to the national government. The integration of ENSO forecasting into crop protection advisory systems represents a particularly high-value near-term opportunity to reduce the vulnerability of Indian agriculture to climate-driven biotic stress and should be prioritised as a cornerstone of climate-smart agriculture policy.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine
Volume 04, Special Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-21

ECO-FRIENDLY SOIL AMENDMENTS FOR HIGH-YIELD OILSEED FARMING

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1. Introduction

Agriculture is undergoing a vital transformation, shifting from high-synthetic input models to regenerative ecological restoration. Decades of intensive cultivation have severely degraded soil microbiomes and depleted organic matter. Consequently, structural and biological soil amendments are no longer optional; they are essential to restore soil Health and future-proof oilseed crops. While chemical fertilizers (like standard N-P-K) give crops a quick, short-term boost, they don't actually feed the soil itself. Over time, relying too heavily on them ruins the soil's health, making it overly acidic, forming a hard crust on the surface, and destroying its natural texture. Ecological farming focuses on bringing the soil back to life. By using organic options like manure, vermicompost, biochar, and biofertilizers, farmers can give crops the nutrients they need while also helping roots grow deeper and trapping carbon in the ground for the long term.

2. Why Amendments are Essential for Oilseeds?

2.1. Why Oilseed Crops Need Good Soil Oilseed crops like mustard, sunflower, soybean, and groundnut are incredibly sensitive to the ground they grow in. Their overall health, how much they produce, and even the amount of oil they yield depend directly on the condition of the soil.

2.2. The Demand for Specific Nutrients To actually make fat and produce plenty of oil, these crops need a careful mix of extra nutrients like Sulphur, Calcium, and Zinc. Natural, biological amendments release these nutrients slowly and steadily throughout the plant's life. This helps the crops use fertilizers much better and makes the plants a lot tougher against stress.

3. Nutrient Dynamics of Oilseeds

3.1. The Sulphur Imperative: This nutrient is playing and controlling the oil synthesis process in most of the oilseed crops. It also required for the production of vitamins, oils, and proteins. The prevalent Sulphur-containing amino acids include homocysteine, cysteine, and methionine; however, proteins mostly contain cysteine and methionine. In general, 40 kg/ha Sulphur application is recommended in rapeseed mustard crop and 20-30 kg/ha is required for soybean crop. Enhancement in Soil Organic Carbon improves the S level in soil, however N:S ratio 6-8:1 and C:N:S 120:10:1 are ideal for improving the S availability in soil solution.

3.2. Micronutrient Demands: Crops like soybean and groundnut rely heavily on micronutrients especially Iron, Boron, and Zinc. Micronutrients act as catalysts in enzymatic reactions and are crucial for the nodulation process in legumes, which aids in nitrogen fixation. B facilitates seed setting, stomata opening, viability of pollen and also uptake of other nutrients like Ca in groundnut. Deficiency in Zn can lead to stunted growth, poor leaf development, and reduced seed production in mustard plants.

4. The Yield Gap: Soil Structure & Water Constraints

Drought and Oil Loss: Oilseed crops easily get stressed by dry weather, especially when flowering and growing seeds. If the soil can't hold water, the plants do not get the steady moisture they need, which directly affects seed weight and oil production.

Hard Soil and Weak Roots: When soil forms a hard crust on top. This stops roots from growing deep into the ground, making it hard for the plant to find water and nutrients buried further down.

Suffocating Roots: Packed soil doesn't have enough air spaces. If water pools on top, the soil gets waterlogged, cutting off the oxygen supply to the roots. This literally suffocates the roots and stops the plant from absorbing nutrients.

5. Organic Amendments: "The Carbon Builders"

Compost- It is the aerobic breakdown of plant residues and stems, kitchen waste, animal dung and biodegradable waste. It also contributes significantly to building soil organic carbon, which is critical for long-term soil health. Compost has been shown to reduce disease incidence and buffer pH levels, making it highly valuable in both organic and conventional agriculture.

Biochar- Biochar is a stable, carbon-rich substance produced by pyrolyzing organic biomass under limited oxygen conditions. It has a highly porous structure that improves soil aeration, moisture retention, and cation exchange capacity.

Farmyard Manure (FYM)- Farmyard manure, also abbreviated as FYM, is Generally composed of animal faeces, urine, leftover feed and any bedding material used in livestock accommodation. FYM provides ample nitrogen, phosphorus and potassium, along with other vital micronutrients.

Green Manure- Nitrogen is the key ingredient for improved fertility of these crops, which is made available via decomposition. Practicing green manuring contributes to the reduction and control of weeds, soil erosion and soil level sedimentation. Enhanced soil structure is also an added benefit to this technique.

6. Inorganic Amendments

Gypsum- Gypsum is primarily used to ameliorate sodic soils, which are characterized by high sodium content. Unlike lime, gypsum does not significantly alter soil pH, making it suitable for pH-neutral or alkaline soils. It also supplies Sulphur, an essential secondary nutrient.

Lime- Lime is a commonly used amendment in acidic soils. By increasing the soil pH, lime enhances phosphorus and molybdenum and reduces the toxic effects of aluminium and manganese. Lime improves the overall nutrient uptake efficiency and promotes better root development.

7. Mechanism of Action: How Amendments Heal the Soil

7.1. Physical properties

- Organic amendments, in particular improves soil structure, better soil aggregation, enhance water holding capacity, maintains optimum soil temperature, reduces bulk density, increases porosity favorable for extensive root growth and development to extract plant nutrients**.**
- Organic amendments stimulate microbial activity, which secretion of Exopolysaccharides improve soil structure and other compounds like hyphae enhances soil aggregation and stability.
- Adding FYM alongside regular fertilizer lowers bulk density much better than

using fertilizer alone because the manure creates more pore space, adds organic carbon, improves root growth, and lightens the soil.

- Using compost made from municipal solid waste improves the soil's structure and pore distribution. This helps water move smoothly through both heavy clay loam and sandy soils.
- Organic matter acts like a natural cement, binding soil together into larger clumps that resist being moved by wind or water erosion.
- Agricultural Gypsum this works to reduce soil density. Its calcium and sulfur act as binders to help neutralize and stabilize the soil.
- In a Soybean field adding 3 T/ha of mustard crop leftovers along with gypsum cut water runoff by 26% and soil loss by 29%.

7.2. Chemical properties

- Adding organic materials boosts the soil's cation exchange capacity. This makes essential nutrients more available to plants, directly improving soil fertility.
- Some materials are rich in calcium and basic cations, creating a "liming effect" that raises pH and boosts helpful microbes in acidic soils.
- Some other lower soil pH by releasing humic acids as they break down through the nitrification of ammonium.
- Adding 5 tons per hectare of FYM along with the (RDF) increased soybean grain yields by 13%.
- Organic amendments stop phosphorus from getting chemically bind up by aluminum, iron, calcium and clay allowing both nutrients to release slowly and steadily to the plants.
- Applying municipal biosolid waste compost just once every 4 years significantly improves the soil's phosphorus supply, besides improves rain water use efficiency of oilseed crops.

7.3. Biological properties-

- Soil microbes are essential for keeping soil healthy. Act as natural recyclers, breaking down nutrients and binding them in the soil so plants can easily uptake.
- Adding organic matter gives soil microbes a boost of energy and food. This naturally brings biodiversity, helps plants grow, and even suppresses crop diseases.
- When soil is damaged by too much salt or alkaline buildup, its biological life shuts down. Microbe population drop, natural recycling stops, and crop yields crash.
- Applying of Sesbania green manure boosts Soil Microbial Biomass Carbon (SMBC) by 90%, increased microbial breathing by 104%, and increases enzyme activity (DHA) by a massive 265% compared to untreated soil, while also trapping more carbon.
- Sodic black soils easily degrade, but using green manure is a fantastic, low-cost alternative to expensive chemical gypsum to fix them, boost crop yields, and keep the ecosystem sustainable.
- Organic matter produces natural acids that lower high soil pH and reduces exchangeable sodium percentages which helps in fixing of Alkaline/Sodic soils.

8. Impact on Oilseed Yield and Quality

Accelerating Oil Synthesis: The Lipid Pathway

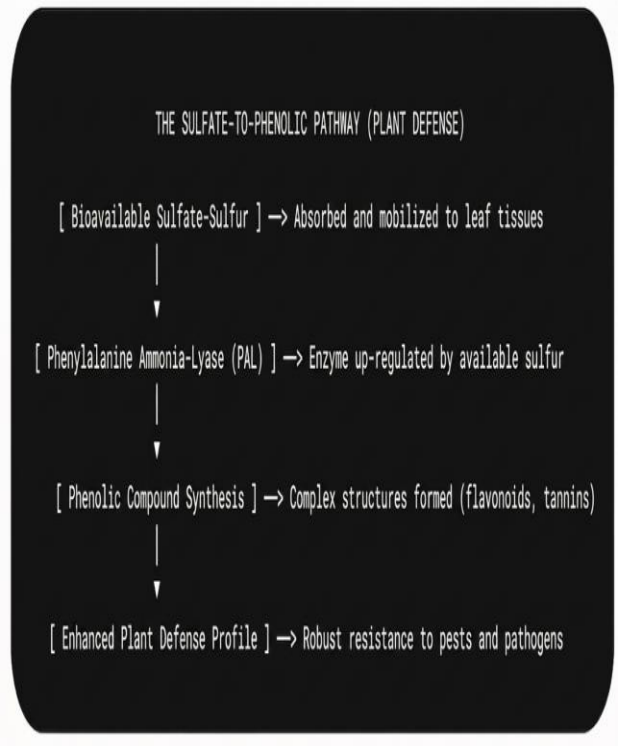
- Making vegetable oil inside a growing seed is a delicate, highly resource-intensive biochemical chain reaction.
- To successfully build fatty acids and lipids, oilseeds must have a continuous, uninterrupted stream of key raw materials most notably carbohydrates, phosphorus, and sulphur.
- "Sulfate-to-Lipid Pathway"

i. Bioavailable Sulfate-Sulfur is absorbed efficiently by the plant's roots.

ii. This activates the Acetyl-CoA Carboxylase enzyme within the developing seed.

iii. Fatty Acid Synthesis builds out lipid chains via metabolism.

iv. This results in Maximized Seed Oil Content for a high-quality, premium harvest.



9. Cultivating Abiotic Stress Tolerance

Environmental Stress	Crop Impact (Without Amendments)	Shielding Action of Eco-Friendly Amendments
Drought & Water Scarcity	Causes severe wilting, vascular collapse, and widespread dropping of flowers and pods.	**Porous Sponge Effect:** Biochar and humus store water deep in the root zone, keeping plants hydrated up to 14 days longer during dry spells.
Soil Salinity & Sodicity	Leads to toxic sodium buildup and osmotic shock, leaving roots unable to absorb water.	**Ion Displacement:** Gypsum breaks up toxic sodium arrays and replaces them with calcium to restore healthy osmotic pressure.
Thermal Spikes (Heat Stress)	Accelerates soil water evaporation and causes the root zone to overheat.	**Thermal Insulation:** Surface organic matter acts like a blanket over the soil, cooling the root zone and protecting sensitive microbe activity.

10. Future research gaps

- Dependence on Rainfed Systems: Over 70% of oilseed cultivation relies on rainfall rather than controlled irrigation.
- High Initial Costs: Transitioning to sustainable methods often requires capital-intensive infrastructure, such as drip irrigation, bio-fertilizers, mechanical equipment to overcome labour shortages.
- Information & Knowledge Gaps: Small and marginal farmers often view organic or bio-intensive pest control as too complex, which increases their risk aversion.

11. Conclusion: Cultivating a Resilient Future

The intensive reliance on synthetic fertilizers has pushed global agricultural soils to an ecological breaking point, systematically depleting organic matter and fracturing the delicate subterranean microbiomes required for healthy plant growth. This structural collapse is especially critical for oilseed crops like rapeseed, soybean, and mustard, which possess demanding lipid-synthesis pathways that require a structurally sound, sulphur-rich soil environment. By transitioning away from short-term chemical dependency toward eco-friendly soil amendments such as carbon-rich biochar, biologically active vermicompost, and targeted mineral correctors like gypsum we can rebuild the soil's architectural matrix, supercharge its nutrient retention capacity, and buffer crops against unpredictable climate stresses.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine

Volume 04, Spcl. Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-22

SMALL TOOLS, BIG YIELDS: MECHANIZING TRIBAL OILSEED FARMING

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1. Introduction

Domestic oilseed expansion has been high on policy agenda as India still imports more than half of the edible oil it consumes. In spite of having Government programmes intended for National Mission on edible oils, we are facing problems in making it possible on ground for greater output of groundnut, mustard, sesame, and Niger seed. Oilseed cultivation is carried out by small, tribal and marginal farmers, who work across plots which are hilly and uneven, scattered across the eastern ghats belt of southern Odisha.

When almost every task depends on human effort in these communities, it is very difficult to have enough yields. Also, when growing oilseeds is a way of sustaining a rainfed household economy rather than thinking it as a business decision, low yield and poor seed quality are the obvious outcomes. During the crucial times, i.e., sowing while the soil still holds monsoon moisture and harvesting before pods shatter, there is shortage of labour. When is the most required, farms run short of hands. Guaranteed local wage work under MGNREGA pull labour away precisely when it is needed most, pushing peak- season wages up sharply and making hired labour unaffordable for anyone farming a small plot.

Next is the requirement of appropriate tools which makes the work easy. This is the gap that scale appropriate mechanization is meant to close. There are problems that drive the case for tools which are built exactly for this terrain. There is no use of conventional tractors above 45 HP or combine harvesters because they cannot be driven on narrow terraced fields and steep gradient, even if they fit, a marginal household has no benefit in buying it. Instead, category of lighter, lower powered, inexpensive implements works better. Problems arise during getting the seed into ground while moisture lasts, cutting down losses after harvest, and easing the physical toll on tribal women, who carry out the bulk of manual field work.

2. Land Preparation and Sowing: Matching Tools to Terrain

Land preparation and seeding is the first weak link in the process of oilseed cultivation. Oil seeds like mustard and groundnut need a steady plant stand, which requires sowing of seed at a consistent depth. Yet most farmers till now use broadcasting method of sowing that makes the anchoring of plants weak, thus reducing the yields. The terrain doesn't allow the use of full-sized machines like tractors, which is why this stage requires small machineries.

2.1. Walk-Behind Power Tillers

An 8-12 HP walk behind power tiller is one of the best replacements for tractor in the broken ground. As illustrated in figure 1, it is light enough to turn within a narrow terrace area and runs on a little fuel. It makes seedbed for mustard in a single pass. Farmers using this machine can finish the land preparation in half the time, and can sow the seeds when the soil moisture is still

intact. Light impression of the machine doesn't increase the soil compaction further.

2.2. Manual Multi-Crop Seed Drills

Row sowing instead of hand broadcasting doesn't require any expensive machinery. Simple single or two row inclined plate planters, pushed or pulled by hand, meter out seeds at equal intervals, using a simple ground wheel mechanism as shown in figure 2. Bolder seeds like groundnuts are saved from seed coat damages. As it reduces the overcrowding of seeds, it lowers the total seed rate upto 30%, overally contributing to lowering of total cost of production.

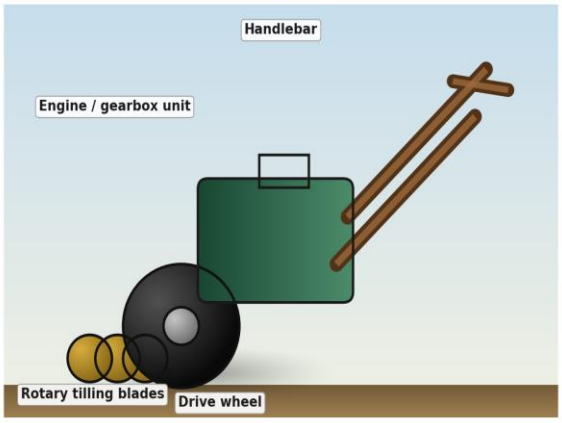


Figure 1. A walk-behind power tiller, showing the engine unit, rotary tilling blades, and the handlebar used to guide it across narrow terraces.

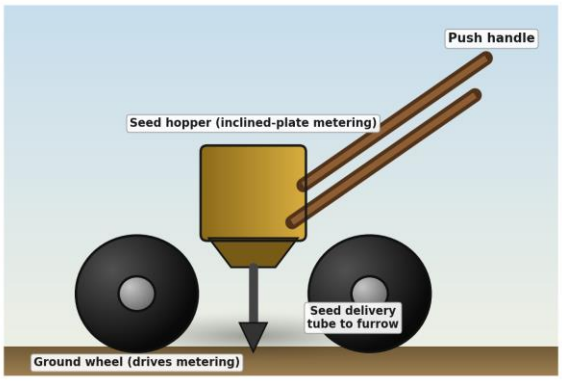


Figure 2. A manual inclined-plate seed drill, where the ground wheels drive the seed-metering mechanism in the hopper and a delivery tube drops seed into the furrow.

2.3. Ridge-and-Furrow Adaptations

Oilseeds are much sensitive to both waterlogged and extended dry spells. A simple inexpensive ridging attachment can help farmers make a ridge and furrow system that can drain the excess water as well as retain the appropriate amount of moisture for the standing crop.

3. Reducing Drudgery in Weeding and Inter-Cultivation

Weed control is one the most labour demanding and costly phase in the production. While oilseeds grow at a slow rate in the initial days, making them exposed to crop weed competition. The critical period of 20-45 Days after sowing is most important, and missing this window cuts the yield to half. Tribal households handle this period using hand-held khurpi tools, a common approach that demands more labours, and an uncomfortable squatting posture that results in physical harm of body.

During the weeding period, the area shares the same pool of labourers that drives the wage further high. Herbicides use remains limited in these areas due to lack of water for spraying and minimal training in safe handling of chemicals. Thus, mechanical weeding gives a more realistic approach.

3.1. Wheel Hoes and Cycle Weeders

A push type cycle weeder, as shown in figure 3 that is fitted with sweep blades or rigged teeth at the back, is used on small terraced plots. This let the individual work upright shifting the load from lower back to arms and legs for more

efficiency. A single operator can cover the plot far faster than labours, decreasing the cost and keeping the work physically lighter.

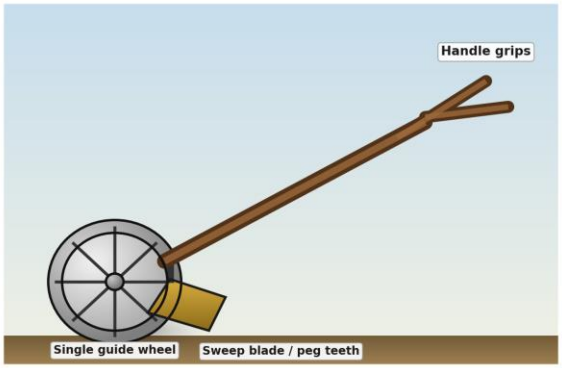


Figure 3. A push-type wheel hoe, with its single guide wheel, long handle grips, and a sweep blade attachment for cutting weeds at ground level.

3.2. Lightweight Motorized and Battery Weeders

Where the crops are grown in a single row, a small 1.5-3 HP battery Powered weeder fitted with fitting heads shown in figure 4 works efficiently between the rows. Most of them weigh between 10 kgs, keeping them manoeuvrable in tight spaces. As they chop weeds on the topsoil, it leaves behind a thin mulch layer that helps to retain moisture in the soil during dry spells.

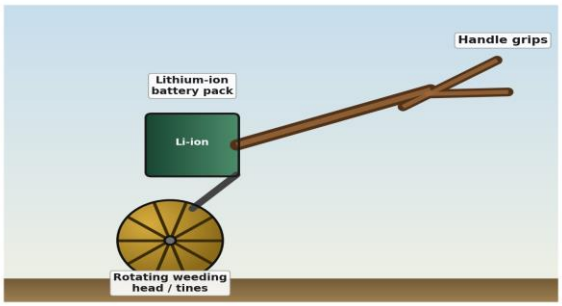


Figure 4. A lightweight battery-powered weeder, with a lithium-ion pack, a long shaft and handle grips, and a rotating tine head for between-row weeding.

3.3. The Gender Dimension

In these regions, most of the intercultural works are carried out by women, and using tools that are not ergonomics in design contribute to back and neck injuries. Using upright, lighter mechanical hoes not just increase the productivity, but also reduces the physical strains, speeds up the work even when the labour is scarce.

4. Harvesting, Post-Harvest Handling, and Ground Realities

Harvesting and Post-harvest processing of oilseed in one of the most crucial phases. Crop like mustard and soybean both have a narrower harvest window, and any delay in the harvesting due to shortage of hands leads to over drying of pods that shatters the grain during handling, throwing away grains even before it reaches the buyer. However, groundnut gives a different problem. Lifting the pods by hand from a dry, unirrigated plot leaves a descent share of pods underground, cutting down a significant part from the yield.

Once harvested, the tribal areas still use traditional method of beating the crop bundles against the logs, and groundnut shelling is done by hands or by stones leaving sore hands and sometimes injuries. Heavy machineries are not affordable for individuals and also have physical restrictions to reach the villages along narrow, unpaved tracks, making smaller, portable processing equipment essential.

4.1. Appropriately Scaled Harvest and Processing Equipment

- Walk-behind reapers (3-5 HP): A small mechanical reaper shown in figure 5, usually 3-5 HP can be used for crops like mustard that

stand upright. It can cut roughly an acre of plot in under two hours, this replacing the sickle.

- Portable multi-crop threshers: As shown in figure 6, a compact axial flow unit, that can be towed behind a power tiller or can be run by small Motors, can be brought directly to field, avoiding cost and effort of hauling of unthresed crop over long distances on hilly track.
- Foot-pedal or small electric groundnut decorticators: These can process around 45 kgs of pods per hour against roughly 4 kgs by hands, keeping kernels intact, sparing workers hand injuries and getting produce to markets faster.

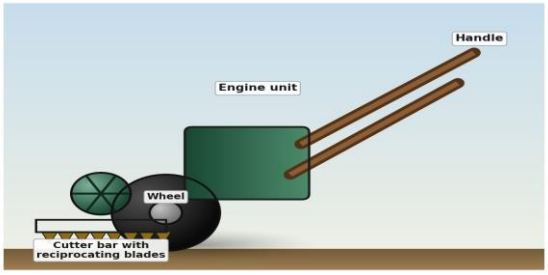


Figure 5. A walk-behind reaper, with its reciprocating cutter bar, star-wheel reel, and handle used to guide the cut across standing mustard**.**

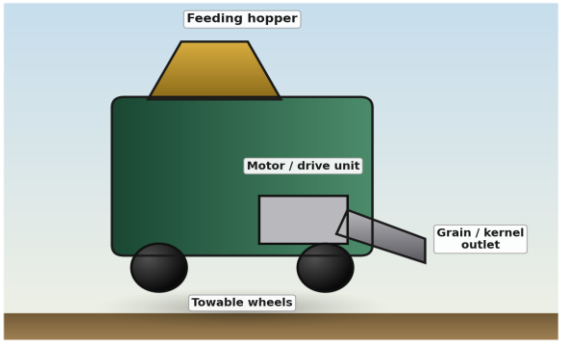


Figure 6. A portable multi-crop thresher, showing the feeding hopper, motor/drive unit, towable wheels, and grain outlet chute.

4.2. Sharing the Cost: Custom Hiring Centres and FPOs in Southern Odisha

In hilly districts like Koraput, main constraint is the individual households can't afford these equipments on their own. Custom Hiring Centres (CHCs) and Farmer Producer Organizations (FPOs) have stepped in as the practical way around this. Rather than every farmer buying these equipments, CHC's set up with support from schemes like Sub-Mission on Agricultural Mechanization, acquired shared equipments and renting it out to ordinary farmers on hourly rates.

5. Policy Support and the Way Forward

Introducing machine alone don't ensure adoption. Tribal community lacks mechanical literacy, also suffers physical isolation, all of which shape how mechanisation policy needs to be delivered.

5.1. Subsidy and Institutional Delivery

The central government offers subsidies in the range of 40-50 percent on power tillers, manual planters and small threshers, under the Sub- Mission on Agricultural Mechanization. Its share is rising to as much as 80 percent for registered women's self-help groups and tribal farming clusters under community-focused schemes. The way which keeps upfront cost from becoming a barrier is equipment bought through these subsidies is generally pooled and managed collectively rather than handed to individual buyers. Farmers can receive improved seed varieties and basic training in operating the equipment together, rather than as separate, disconnected efforts by linking the machinery push with the National Mission on Edible Oils.

5.2. What Still Needs Fixing

- Local repair capacity: Most of the equipment are used for away from where they are manufactured. So, a breakdown in the machine can stall the work for several days. Training local youths as certified technicians and having local repair points would shorten the downtime considerably.
- Design that accounts for women operators: As most the sowing and intercultural operations are done by women, Machine designed ergonomically and lightweight will help the women workers.
- Stronger machinery banks run by FPOs: Giving Farmer Producer Organizations easier access to low-interest loans would let them build village-level equipment pools, so farmers can rent what they need without depending on private operators.

6. Conclusion

For the sector to stay viable, moving away from manual cultivation toward mechanization scaled to fit small, sloping, tribal plots are not optional. The way in which tools can protect harvests from weather risk, bring down production costs meaningfully is through shared models like CHCs and FPOs rather than sold to each household individually as large machinery has no place on terrain like that of Koraput's. This way also lightens the physical burden being carried by tribal women, while supporting the country's broader push toward edible oil self-sufficiency.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine

Volume 04, Spcl. Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-23

PRECISION AGRICULTURE: A NEW PATH FOR TRIBAL OILSEED FARMERS

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Introduction

Rapeseed and mustard edible oils form a major part of India's edible oil production, accounting for 36% of the total production during the rabi season, and are critical for edible oil security. National yields have increased, while tribal areas of Jharkhand, Chhattisgarh, Madhya Pradesh, and the northeast hills have seen loss of productivity caused by the dependence on rain, soils, and infrastructure, are limited. While the low-input farming methods and biodiversity are longstanding features of these areas, rising problems of unpredictable post-monsoon rains and pest attacks (such as aphids, Alternaria blight) to production are increasingly affecting them.

Precision Agriculture (PA) is a data informed management approach which allows to address a field as a whole or to address every specific part of a field with precision-based management instructions. Because of the variations in factors such as soil type, moisture, and pest pressure throughout a field, PA apply the right input at the right time and right quantity which is a four-step cyclic process of data collection, analysis, variable rate application (VRA), and evaluation. The technologies that enable this include GPS, GIS, remote sensing and variable rate technology (VRT). PA is well adapted to oilseed crops (canola, soybeans, sunflowers, mustard, groundnuts) where optimising nutrition, moisture and harvest time is particularly effective for improving yield and profitability and is especially effective in these crops, which are highly sensitive to these management factors. PA has three important advantages for oil seed producers: cost-effectiveness, quality assurance and environmental responsibility. PA wouldn't replace traditional methods but it can stabilise them with a range of techniques that are site-specific and cost-effective without any costly machinery such as a drone or autonomous tractor. With appropriate technology and knowledge of the local people, PA can make mustard and rape cultivation more efficient and sustainable, while protecting the delicate hill ecosystem. Precise methods in tribe's lands will need a different and resource-poor strategy rather than heavy and costly machinery. By combining the technology advancements with the traditional knowledge of the indigenous people, it will be possible to transform the tribal oilseed farming practice from a risk with nature to a profitable, efficient and sustainable venture.

Why is there a need for Oilseed to have a precision framework?

Table 1. Difference Between Traditional Blanket farming and Precision- driven tribal farming

Traditional 'Blanket' Framing	Precision-driven Tribal Farming
Uniform input application	Soil-specific micro-dosing
More expensive and More waste	A set of relatively inexpensive sensors and GIS maps
Sensitive to climate change	Resource conservation (water)
Minimal/ Conventional: highly dependent on a large amount of general	Data-Integrated: Leverages low-cost sensors, solar-powered IoT devices

hand labour or standard uniform mechanical equipment.	and mobile technology made simple for small/fragmented holdings.
Most appropriate for flat, large, overgrown fields.	Optimized specifically for broken, hilly and degraded land in tribal areas.
Can be intensive and focused on raw yield, leading to long-term soil degradation.	Emphasis on sustainability, involving the use of new technology and traditional agroforestry with organic approaches and changing the way cultivation is managed.

As mentioned above Traditional farming needs uniform input application and it is more expensive and more generate waste and also sensitive to climate change whereas Precision driven agriculture is soil specific and inexpensive also conserves natural resources. This is particularly the case with oilseeds as compared to normal cereals. The successful cultivation of oilseeds is dependent on very exact farming practices in three areas in particular:

i. Foliar development vs oil yield:

Excess N fertilizer may encourage vegetative growth, while having the unhelpful side effect of lowering oil content in oilseed crops like rapeseed, or sunflower.

ii. Very shallow planting depths:

Tiny seeds (such as sesame or canola seeds) require very shallow planting depth. Neither too shallow nor too deep is desirable, shallow planting depths results in low germination while planting too deep exposes plants to bird attack and dry winds.

iii. Delayed harvest:

There will be timing issues with the harvest of oilseeds, as the pods mature different times. If harvested too early, by just a few days, the seeds will not be ripe and will not have the same quality of oil, while too late harvest will result in the shattering of the seeds.

The Revolution is Being Driven by High-Tech Tools

To address these issues, state-of-the-art oilseed production combines a set of sophisticated hardware and software tools throughout the crop's entire life cycle.

GIS-Based Digital Soil Nutrient Mapping

Remote Sensing and GIS provide the exact nutrient content of the soil at a specific area. Rather than following broad fertilization processes, the tribal farmers get customized directions through Digital Soil Health Cards. Then they apply precisely the values of Sulphur and Boron-essential nutrients for getting maximum oil content in Niger and Mustard crops.

High Precision Sowing and Autosteer System

These Autosteer systems in tractors use GPS technology to ensure the accuracy of field placement to within centimetres. In the case of oilseed crops, this technology is used along with air-seeder drills. Human error is eliminated during sowing, the placement of plants is accurate and the seed-to-soil depth is accurate, increasing the germination rate by 15%-20%.

Smart Seed Coating Technology

Small, light seeds such as sesame and niger are prone to washing off or clumping irregularly in flash rain or in irrigation in steep hillside fields, because of the small size of the seed. The scientists from Navsari Agricultural University and Central University of Odisha, Koraput, have jointly invented a solar-powered seed pelleting machine which is specifically developed for the terrain of Koraput.

It provides fertilization, growth stimulants and crop protection nutrients to each kernel, thus increasing the weight and keeping the seeds on slopes and providing maximum growth.

Variable Rate Technology (VRT) For Optimized Nutrition

This technology is used to segment a field into several areas based on data gathered from yield sensors and soil nutrition sensors that were used in previous years. By balancing localized nitrogen application, VRT actively protects against the unintentional decrease of oil due to excess fertilizer.

Weather-Based Agro-Advisory Services

Timing is crucial to ensure accuracy of Hyper-Local Weather and Pest Forecasting (AI and IVR) for oilseed crops like Sunflower and Mustard, which are susceptible to water stress and pests/diseases (Aphid, Powdery Mildew). The Ama Krushi forecast system is a precision tool which delivers timely alerts of weather anomalies to the tribal farmers, at the cluster-village level, through telephone voice messages. This allows farmers to perform operation like planting that make use of leftover soil moisture in the soil after the harvest of rice crops and harvesting to prevent pod-shattering.

Localized Irrigation in Uncultivated Winter Paddy Lands

Water scarcity during the post-monsoon Rabi season restricts the oilseed production on upper ridges. Gravity drip irrigation, solar micro-sprinklers and cheap soil moisture sensors provide water to the roots of Groundnut and Sunflower instead of the fields being flooded. This precision method is designed to make the water go further, enabling tribal farmers to produce a viable second-crop in the face of limited water access.

Targeted Rice-Fallow Mapping Based on Remote Sensing

Satellite images and data-collection Apps, map the exact boundaries of rice stubble fields and identify moisture-holding bare slopes after the monsoon. This mapping information is used by government to target these high potential areas and offer hybrid seed packages for zero till Mustard or Sunflower in the right areas, where the chances of success are mathematically the greatest.

Multispectral Remote Sensing

The use of Drone and Satellite Scouting through the use of remote sensing technology to check on the stresses of the crop, through the use of unique Vegetation Indices.

Smart Harvesting and Moisture Monitoring

Oil seeds yield monitoring is a process that takes place in the oil seed combine harvesters that measures moisture and weight during harvest. Oilseeds are prone to spoilage at high moisture, so real-time moisture monitoring will give information to help decide which parts of the field have low enough moisture to drill directly without the need to dry. The rest are for storage and require additional drying.

Conclusion

An adoption of conventional agriculture to precision agriculture has its own set of savings in resources and increased production. Through the use of GPS technology and analysis of data, the amount of waste in terms of fuel, seeds and chemicals is lowered by a maximum of 20%. This occurs in conjunction with specific fertilization and irrigation that have been seen to boost yields by 10%-15% thus providing the much-needed boost to the world edible oil chains. Through the use of these customized data sets, oil seed growers will be able to safeguard their profits, maximize quality of grain and ensure environmental sustainability.

Table 2. Vegetation Indices (VIs) and Their Primary Function of Multispectral Remote Sensing

S. No.	VIs	Primary Function in Oilseed Farming	Reference
1.	Normalized Difference Vegetation Index (NDVI)	General measure of vegetation greenness and vigor using red and NIR reflectance; widely used for canopy density and crop health monitoring.	Parida *et al*., 2024a
2.	Normalized Difference Moisture Index (NDMI)	Tracks vegetation moisture/water stress using NIR and SWIR reflectance; often applied to forest and crop moisture mapping.	Wilson & Sader, 2002
3.	Green Normalized Difference Vegetation Index (GNDVI)	Substitutes areen for the red band to improve sensitivity to chlorophyll concentration and detect early stress before NDVI responds.	Gitelson *et al.,* 1996
4.	Normalized Difference Red Edge (NDRE)	Uses the red-edge band instead of red to detect nitrogen/chlorophyll status in mid-to-late season when canopy is dense and NDVI saturates.	Parida *et al*., 2024b
5.	Enhanced Vegetation Index (EVI)	Corrects NDVI for atmospheric and soil/canopy background noise using a blue-band term, improving accuracy in high-biomass canopies.	Huete *et al*., 2002
6.	Soil Adjusted Vegetation Index (SAVI)	Minimizes soil brightness influence on the vegetation signal via a soil adjustment factor (L), useful in sparse-canopy areas.	Parida *et al*., 2024a

7.	Modified Soil Adjusted Vegetation Index (MSAVI)	Self-adjusts the soil factor dynamically, further reducing soil noise and improving sensitivity at low vegetation cover.	Qi *et al.,* 1994
8.	Normalized Difference Water Index (NDWI)	Estimates vegetation liquid water content using NIR and SWIR bands; used for canopy water-status and drought monitoring.	Gao, 1996
9.	Moisture Stress Index (MSI)	Ratio of SWIR to NIR reflectance used to detect canopy water stress and leaf water content changes.	Rock *et al.*, 1986
10.	Chlorophyll Index Green (CIgreen)	Estimates relative chlorophyll content using NIR and green bands, sensitive to pigment changes from stress or senescence.	Gitelson *et al.,* 1996
11.	Chlorophyll Index Red-Edge (CIred-edge)	Estimates canopy chlorophyll content using NIR and red-edge bands; more robust than CIgreen at higher chlorophyll levels.	Gitelson *et al.,* 2003
12.	MERIS Terrestrial Chlorophyll Index (MTCI)	Surrogate for red-edge position, used to estimate canopy chlorophyll content from MERIS-type sensor bands.	Dash & Curran, 2004
13.	Plant Senescence Reflectance Index (PSRI)	Detects leaf senescence, fruit ripening, and carotenoid/chlorophyll ratio shifts using red, blue, and NIR bands.	Merzlyak *et al.,* 1999
14.	Bare Soil Index (BSI)	Differentiates bare soil from vegetated/built-up areas using red, blue, NIR, and SWIR bands; used in land-cover classification.	Rikimaru *et al.,* 2002

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine

Volume 04, Spcl. Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-24

IMPACT OF AI, DRONES AND MOBILE APPS IN OILSEED AGRICULTURE

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Abstract

The agricultural sector is experiencing a major transformation through the integration of digital technologies that improve productivity, sustainability, and resource-use efficiency. Oilseed crops, particularly rapeseed-mustard, face increasing challenges due to climate change, pest outbreaks, declining soil fertility, and water scarcity. Conventional farming practices often fail to address the spatial and temporal variability present within agricultural fields, leading to inefficient use of resources and reduced profitability. Digital agriculture offers innovative solutions through the application of artificial intelligence (AI), drones, remote sensing, Geographic Information Systems (GIS), Internet of Things (IoT)-based sensors, mobile advisory applications, and data analytics. These technologies enable real-time monitoring of crop health, early detection of stress conditions, precision input management, and predictive decision-making. This article explores how digital technologies are transforming oilseed production systems from reactive management approaches to predictive and preventive agriculture. It discusses practical applications, real-world examples, benefits, challenges, and future prospects of digital agriculture in rapeseed–mustard cultivation. The integration of technologies from sky-based observation systems to soil-level sensing networks is creating more intelligent, efficient, and sustainable farming systems capable of addressing future food security challenges.

Keywords: Artificial intelligence, Precision agriculture, Rapeseed–mustard, Remote sensing, GIS, IoT

Introduction: Yield Is No Longer Enough

Agriculture has always been fundamental to human civilization, providing food, nutrition, employment, and economic stability. However, the demands placed on agriculture are rapidly increasing due to population growth, urbanization, changing dietary patterns, and climate variability. Oilseed crops are particularly important because they contribute significantly to edible oil production, industrial applications, livestock feed, and biofuel industries. Among these crops, rapeseed–mustard occupies a prominent position in global agriculture and serves as a major source of vegetable oil in many developing countries, including India (FAO, 2021).

Despite its importance, rapeseed–mustard production faces numerous challenges. Rising temperatures, erratic rainfall, declining groundwater resources, increasing pest and disease incidence, and escalating input costs have reduced the effectiveness of traditional agricultural practices. Farmers often rely on generalized recommendations and visual observations, which may not adequately address field variability or rapidly changing environmental conditions (Gebbers & Adamchuk, 2010).

The concept of digital agriculture has emerged as a promising solution to these challenges. Digital agriculture combines advanced technologies such as artificial intelligence (AI), machine learning, drones, remote sensing, Geographic Information Systems (GIS), Internet of Things (IoT) sensors, cloud computing, and mobile-based advisory

systems to improve agricultural decision-making (Wolfert et al., 2017). These technologies collect and analyze real-time data from fields, enabling farmers to make precise and informed decisions regarding irrigation, nutrient management, pest control, and harvesting.

Unlike conventional farming approaches that respond to problems after they become visible, digital agriculture promotes predictive and preventive management. The integration of aerial imaging, sensor networks, and AI-driven analytics allows farmers to identify emerging problems before significant crop damage occurs (Liakos et al., 2018). This transformation represents a shift from intuition-based farming to data-driven agriculture, where every decision is supported by scientific evidence and real-time information. The phrase "From Sky to Soil" perfectly captures this technological transformation. From satellites orbiting hundreds of kilometers above the Earth to sensors embedded in the root zone of crops, digital technologies are creating interconnected agricultural ecosystems that enhance productivity, sustainability, and resilience.

Predict, Prevent and Protect Through Digital Technologies

One of the most significant contributions of digital agriculture is its ability to shift farming from reactive management to predictive and preventive management. Traditionally, farmers identify problems only after visible symptoms appear. By that stage, yield losses may already have occurred. Digital technologies overcome this limitation by continuously monitoring environmental and crop conditions and providing early warning signals (Rose et al., 2021).

- The first stage is prediction. Drones, weather stations, satellite imagery, and IoT sensors collect large amounts of real-time information related to crop growth, soil moisture, canopy temperature, rainfall, and nutrient status. AI-based analytical tools process these datasets to identify patterns associated with pest outbreaks, disease development, nutrient deficiencies, and water stress (Liakos et al., 2018).
- The second stage is prevention. GIS-generated maps identify spatial variability within fields and help farmers implement site-specific management practices. Instead of applying fertilizers, pesticides, and irrigation uniformly across the field, inputs can be applied only where required, improving efficiency and reducing costs (Sishodia et al., 2020).
- The final stage is protection. Thermal cameras, multispectral sensors, and remote sensing platforms continuously monitor crop health. Early detection of stress conditions allows timely interventions, reducing crop losses and maintaining productivity (Mulla, 2013).

Artificial Intelligence and Predictive Analytics

Artificial Intelligence has become one of the most influential technologies in modern agriculture. AI systems are capable of processing large volumes of data from diverse sources and generating accurate recommendations for crop management (Jha et al., 2019).

Machine learning algorithms analyze historical weather records, soil characteristics, crop growth patterns, and pest incidence data to predict future outcomes. These predictive models help farmers optimize sowing dates, irrigation schedules, fertilizer applications, and pest management strategies (Fig. 1).

In rapeseed mustard production, AI can assist in forecasting aphid infestations, one of the most serious insect threats affecting crop productivity. By integrating weather variables, crop growth stages, and historical pest data, AI models can provide advance warnings that allow farmers to implement preventive control measures before severe infestations occur.

Microsoft's AI Sowing Application in Andhra Pradesh demonstrated the potential of AI-driven advisory services. Farmers using the platform reported yield increases of approximately 30 percent in groundnut

production due to improved sowing recommendations and weather-based advisories (Pathak *et al*., 2020).

Similarly, IBM Watson Decision Platform for Agriculture combines satellite data, weather forecasts, and crop models to generate hyper-local recommendations. Such systems enable farmers to optimize pesticide applications, irrigation management, and nutrient scheduling while reducing operational risks.

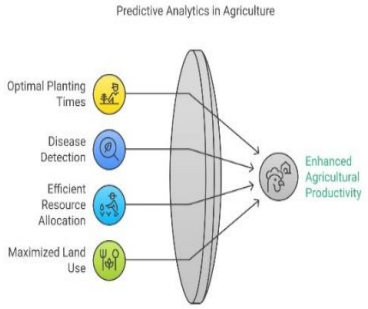


Figure 1: Predictive Analytics in Agriculture

Drones: Eyes in the Sky for Precision Farming

Drones have revolutionized agricultural monitoring by providing rapid, high-resolution observations of crop fields. Unlike traditional field scouting methods that are time-consuming and labor-intensive, drones can survey large areas within minutes and generate detailed information about crop conditions (Zhang & Kovacs, 2012). Agricultural drones are equipped with RGB cameras, multispectral sensors, thermal cameras, and near-infrared imaging systems. These sensors capture detailed imagery that reveals variations in plant health, nutrient status, water stress, and disease incidence (Fig. 2). In rapeseed - mustard fields, drones can detect subtle changes in canopy reflectance before visible symptoms appear. Multispectral imagery is commonly used to calculate vegetation indices such as NDVI and GNDVI, which provide valuable information about crop vigour and chlorophyll content (Parida et al. 2024a, Parida et al. 2024b).

Drone technology supports several precision agriculture applications:

- Early detection of crop stress
- Pest and disease surveillance
- Precision irrigation management
- Nutrient deficiency identification
- Yield prediction
- Variable-rate input application

Studies in Europe have shown that drone imagery can identify stress zones in rapeseed fields earlier than traditional visual inspections. Similarly, Indian researchers have successfully used drones to detect uneven crop growth and pest infestations in mustard fields.

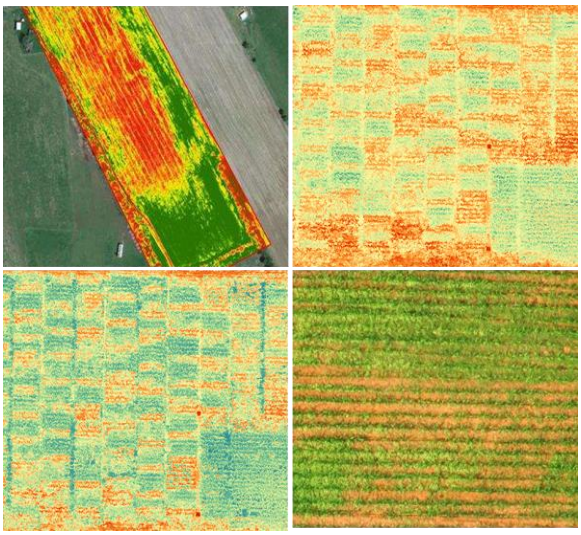


Figure 2: Disease & Pest management Using Drones

Remote Sensing and GIS Applications

Satellite platforms such as Sentinel-2, Landsat, and MODIS provide valuable data for monitoring rapeseed production over large geographical regions. Remote sensing and GIS have become indispensable tools for modern agriculture. These technologies allow continuous observation and analysis of agricultural fields without requiring frequent physical visits

(Sishodia *et al*., 2020). Remote sensing systems collect information using satellites, aircraft, and drones. Sensors capture reflected radiation in visible, infrared, and thermal wavelengths. Because healthy and stressed plants reflect light differently, these data can be used to assess crop health and productivity. GIS integrates remote sensing data with soil information, weather records, irrigation schedules, and topographic characteristics to create detailed spatial maps. These maps help farmers identify field variability and implement site-specific management practices (Acharya, S., & Pawar, S. 2018).

Mobile Advisory Applications for Oilseed Farmers

The widespread adoption of smartphones has transformed agricultural extension services. Mobile advisory applications provide instant access to scientific recommendations, weather forecasts, pest alerts, market information, and crop management guidelines (Rao, 2007).

Several applications specifically support oilseed production:

ANGRAU-KVK Banavasi CFLD: Developed under Acharya N.G. Ranga Agricultural University, this app offers end-to-end information on oilseed production, protection, and market prices directly to your phone (Fig. 3).

Kisan Suvidha: Provides weather forecasts, market prices, and plant protection advisories (Fig. 4).

Oilseeds Kisaan Mitra: A multilingual AI-powered advisory platform developed by ICAR-IIOR (Fig. 5).

Plantix: Uses artificial intelligence to diagnose crop diseases from smartphone images (Fig. 6).

Cropin: Offers predictive analytics, remote monitoring, and digital farm management solutions.

These platforms help bridge the gap between research institutions and farmers, ensuring timely dissemination of scientific knowledge.

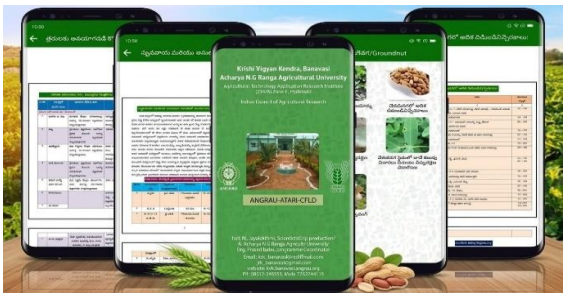


Figure 3: ANGRAU-KVK Banavasi CFLD app



Figure 4 : Kisan Suvidha app



Figure 5 : Oilseed Kisaan Mitra app

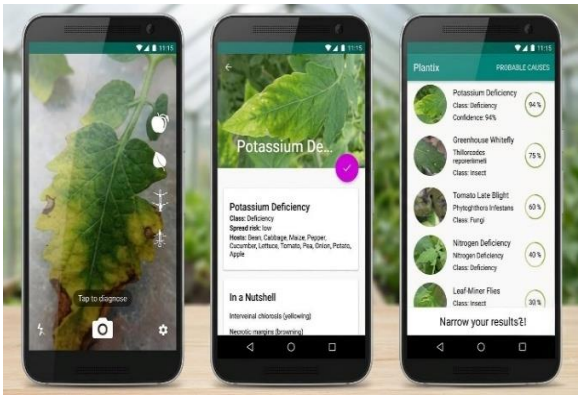


Figure 6 : Plantix app

Sensor-Based Irrigation and Smart Water Management

Water scarcity has become a major constraint in agricultural production. Efficient irrigation management is therefore critical for sustainable oilseed cultivation (Talaviya et al., 2020).

Sensor-based irrigation systems utilize soil moisture sensors, temperature sensors, humidity sensors, and weather stations to continuously monitor field conditions. Data collected from these devices are transmitted to cloud-based platforms where AI algorithms determine irrigation requirements.

The operational sequence follows:

Field Sensors → Real-Time Data Collection → Cloud Analytics → AI-Based Recommendations → Precision Irrigation

When soil moisture falls below optimum levels, farmers receive notifications recommending irrigation. This approach prevents both water stress and over-irrigation.

Benefits include:

- Improved water-use efficiency
- Reduced irrigation costs
- Lower energy consumption
- Enhanced nutrient uptake
- Improved seed yield and oil content

Challenges in Digital Agriculture Adoption

Despite its numerous advantages, digital agriculture faces several barriers to widespread adoption.

Major challenges include:

- High initial investment costs
- Limited digital literacy among farmers
- Poor internet connectivity in rural areas
- Data privacy concerns
- Lack of technical support services
- Limited access to advanced technologies by smallholder farmers

Addressing these constraints requires government support, capacity-building programs, affordable technology solutions, and improved digital infrastructure (Klerkx et al., 2019).

Conclusion

Digital agriculture is fundamentally transforming rapeseed–mustard production systems. Technologies such as AI, drones, remote sensing, GIS, IoT sensors, and mobile advisory applications are enabling farmers to make more informed, timely, and precise management decisions. These tools facilitate early detection of crop stress, optimize resource utilization, improve productivity, and enhance environmental sustainability. Although challenges related to cost, accessibility, and digital literacy remain, continuous technological advancements are making digital agriculture increasingly accessible to farmers worldwide. The journey from sky to soil represents a new era of intelligent farming where every decision is guided by data, every resource is utilized efficiently, and every field becomes more resilient to future challenges.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine

Volume 04, Spcl. Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-25

FROM FIELD TO REFINERY: INTEGRATING MECHANIZATION AND MODERN EXTRACTION FOR OILSEED EFFICIENCY

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Introduction

Oilseed crops constitute one of the most commercially critical agricultural commodities globally, providing essential edible oils, proteins, and industrial raw materials. In India, oilseeds occupy approximately 14.3% of the gross cropped area, yet the country meets nearly 56-63% of its edible oil demand through imports. The global demand for vegetable oils has been gradually increasing due to population growth, changing dietary habits, and expanding industrial applications. India, as the fourth-largest producer of oilseeds globally (after USA, China, and Brazil), cultivates nine major annual oilseed crops: groundnut (*Arachis hypogaea*), mustard/rapeseed (*Brassica juncea*), sesame (*Sesamum indicum*), safflower (*Carthamus tinctorius*), linseed (*Linum usitatissimum*), niger seed (*Guizotia abyssinica*), castor (*Ricinus communis*), soybean (*Glycine max*), and sunflower (*Helianthus annuus*).

Despite its diverse agricultural landscape, India suffers from a severe edible oil deficit, consuming nearly 25 million tonnes annually while producing only 11.2 to 12.18 million tonnes, forcing a heavy reliance on costly foreign imports. This supply gap is primarily driven by three structural constraints: a profound 76% dependency on rainfed cultivation that leaves crops highly susceptible to monsoon fluctuations during crucial growth phases. A substantial post-harvest loss between 2.87% and 7.51% is caused by crude manual harvesting and poor shortage. And a critical workforce deficits during harvest peaks, largely due to workers moving to urban areas, which inflates labor costs and delays critical sowing and harvesting period. So to address these challenges, the Government of India initiated the National Mission on Edible Oils (NMEO) which focuses on two strategic components: NMEO-OP (Oil Palm) and NMEO-OS (Oilseeds). The mission targets increasing aggregate oilseed production from 39 to 69.7 million tonnes by 2030-31. Achieving these ambitious goals requires a cultural evolution toward precision farm mechanization and optimized post-harvest engineering (ICAR, 2023).

2. Precision Tillage and Sowing System:

2.1 Importance of Mechanized Sowing

Traditional manual broadcasting of oilseed seeds results in erratic seed spacing, inconsistent seed depth, and inadequate seed to soil contact. This causes uneven sprouting, uneven plant spacing, and suboptimal plant populations. Mechanized line sowing using seed-cum-fertilizer drills and planters addresses these limitations by ensuring precise seed placement at uniform depth and spacing.

2.2 Primary and Secondary Tillage Equipment

Proper seedbed preparation is fundamental for oilseed establishment. The All India Coordinated Research Project on Farm Implements and Machinery (AICRP-FIM) has developed specialized equipment:

Mouldboard (MB) Plough: Capable of preparing fields up to 45 cm depth, turning and pulverizing soil. It is about 3 times more efficient than traditional animal-drawn plows. The inversion of

soil layers helps incorporate crop residues and kills weeds.



Figure 1: Mouldboard Plough

Sub-soiler: Used for vertical tillage at depths of 40-75 cm once every three years to break hard pans. This allows rainwater to soak into the ground, preserves soil moisture during droughts, reduces surface runoff, and helps prevent collar rot disease in groundnut.



Figure 2: Sub-Soiler

Rotovator: A tractor PTO-driven implement that crushes the clods and incorporates organic residues. It enhances soil aeration by filling pores with air, promoting better root respiration and nutrient uptake.



Figure 3: Rotovator

2.3 Advanced Sowing Equipment:

2.3.1 Tractor-Mounted Inclined Plate Planter

Developed by ICAR-Central Institute of Agricultural Engineering (CIAE), Bhopal, the six-row inclined plate planter represents a significant advancement in crop establishment. Its key features include:

- **Modular inclined plates** featuring custom sized cellular cavities allow for precise seed singulation, preventing physical harm to seeds.
- **Bed-shaping attachment** for raised-bed or broad-bed cultivation, improving soil aeration, drainage during excess rainfall, and water-use efficiency.
- **Ground wheel-driven metering** though chain-sprocket and bevel gear transmission.

Performance parameters (Singh *et al*., 2010): - Field capacity: 0.42 ha/hr (intercropping soybean and pigeon pea in 3:2 ratio on 1550 mm broad beds) - Effective width: 1850 mm - Field efficiency: 64-86.8% - Mechanical seed damage: <2.5% - Uniform plant density: 33 plants/m2 for groundnut at 113 kg/ha seed rate.



Figure 4: Tractor Mounted Inclined Plate Planter

2.3.2 Bullock-Drawn Multi-Crop Planter:

For small-scale farmers with limited capital, this three-row bullock-drawn machine provides a low cost choice. It features three independent modular seed containers with gravity-fed metering driven by a lugged ground

wheel. Field trials demonstrated: - Average field capacity: 0.11-0.23 ha/hr - Field efficiency: 51.1-70% - Cost reduction: 3.5 times compared to hand-metered sowing



Figure 5: Bullock Drawn Multi Crop Planter

2.3.3 Pneumatic Punch Planter

It is a specialized machine used in farming, especially for planting through plastic covers (mulch) or in protected soil. It is known for putting seeds exactly where they need to grow. Its mechanism involves: - A pneumatic metering plate synchronized with an eccentric slider-crank and duckbill mechanism - PTO-driven aspirator blower creating vacuum for individual seed pickup - Slider-crank converting rotational motion to vertical displacement, pressing the duckbill through mulch into soil.

Performance: At 1.7 km/hr with 1 m operational width, it achieves 0.2 ha/hr field capacity, 74% field efficiency, and saves 26 man-days/ha compared to manual mulch sowing.



Figure 6: Pneumatic Punch Planter

2.4 Comparative Economics of Sowing Methods:

Sowing Methodology	Field Capacity (ha/h)	Power Requirement	BCR	Key Advantage
Manual Broadcasting	Very Low	High manual labor	1:1.70-1.77	Minimal capital; uneven stand
Cup-Feed Seed Drill	0.15-0.77	Tractor (>=35 hp)	1:1.90-2.30	Exact depth and spacing
Inclined Plate Planter	0.42-0.65	Tractor (>=35 hp)	1:2.20-2.45	Singulates without damage
Zero-Till Drill	0.20-0.50	Tractor (>=45 hp)	1:2.07	Preserves moisture; saves Rs.1,750/ha

3. Post-Harvest Drying and Storage Technologies

3.1 Thermodynamics of Seed Drying

Freshly harvested oilseeds contain 18-40% moisture, making them vulnerable to metabolic activity, lipid breakdown (rancidity), and fungal growth. Drying relies on heat and mass transfer: warmed air lowers relative humidity, creating vapor pressure deficit that forces internal moisture to the surface for evaporation.

3.2 Safe Moisture and Temperature Limits

Oilseed Type	Harvest Moisture	Safe Storage Moisture	Optimal Drying Temperature
Groundnut (Pods)	20-40%	<7-9%	35-40 degrees C
Soybean	15-25%	8-11%	<47 degrees C
Mustard/Rapeseed	15-20%	8%	30-45 degrees C
Sesame	High (Monsoon)	8-9%	35-40 degrees C
Sunflower	15-20%	<9%	30-50 degrees C

3.3 Drying System:

Traditional Sun Drying: Zero capital cost but uncontrolled, subject to weather variability, contamination, and UV degradation. Rapid surface desiccation causes thermal stress, seed coat cracking, and germination loss.

Fluidized/Spouted Bed Dryers (FBD/SBD): High-velocity heated air suspends seeds, maximizing surface area and heat distribution.

Solar Cabinet Dryers: Rudra and Raheja models use UV-filtered polycarbonate sheets with photovoltaic-powered fans, maintaining 50-80 degrees C while protecting from dust and insects. These preserve aromatic compounds and essential fatty acids.

3.4 Aflatoxin Management in Groundnut

Aspergillus flavus and A. parasiticus produce aflatoxins (B1, B2, G1, G2) - potent hepatocarcinogens. Contamination occurs when pod moisture exceeds 12% in hot, humid conditions.

Prevention strategies: - To stop these molds farmers must protect crops from drought, avoid damaging the pods during digging/threshing, and dry them immediately to reduce moisture below 7-9% within 3-5 days. Store it in HDPE bags (160 micrometer) or double-layered polythene (DLP) bags, creating CO2-rich microclimate that arrests fungal growth

4. Seed Processing, Grading, and Quality Assurance:

4.1 Spiral Separator: Shape-Based Sorting

The spiral separator is a zero-energy machine that separates spherical whole seeds from flat contaminants based on kinetic and centrifugal principles. This process is crucial for cleaning soybeans to prevent oil quality degradation.

4.2 Magnetic Separation

For weed seeds with rough/sticky coats (clover, vetch in canola), seeds are treated with iron powder and moisture. The powder adheres selectively to weed seeds, which are then attracted to a revolving magnetic drum and brushed into waste chutes, while smooth oilseeds fall into the product stream. Capacity: 113-907 kg/ha.

4.3 AI-Driven Optical Sorting

Modern seed sorting uses high speed conveyor belts, controlled illumination, and advanced cameras with AI algorithms (CNNs) and Support Vector Machines (SVM). These analyze size, shape, color, and surface defects at rates of thousands of seeds per second.

FT-NIR Spectroscopy: Non-destructive internal quality assessment at 1450 nm (water molecule absorption) enables instant determination of moisture, protein, and lipid profiles with >98% accuracy.

Indian innovations: Pioneering companies like Agrograde and Sickle Innovations process up to 24,000 quintals daily with >96% defect detection, ultimately cutting labor costs by 40% and reducing post- harvest loss by 90%.

5. Oil Extraction and Refining:

5.1 Physical Pretreatment and Conditioning

Size reduction and flaking: Roller mills rupture cell walls and flakers flatten the material into thin layers (0.2-0.4 mm), maximizing surface-to-volume ratio for easy oil flow and solvent penetration.

Thermal conditioning (Cooking): Heating flakes at 105-130 degrees C for 30-120 minutes with an initial moisture level of 9-14.5%. This heating process works by clumping internal proteins, thinning the oil to reduce its thickness, and merging tiny oil droplets together.

5.2 Mechanical Screw Pressing

The continuous screw press is the industry standard for chemical-free extraction. It consists of a helical wormshaft rotating inside a cage-like barrel of steel bars.

Three operational zones: 1. Feed section: Large, deep screw threads quickly scoop up the raw seeds and move them into the machine.

2. Compression section: The screw threads become smaller and tighter, creating a pressure of 20-30 MPa and frictional heat, that crushes the seeds to extract their oil.

3. Discharge section: The oil drains out through the tiny gaps in the barrel while a special cone squeezes out the leftover dry seed material.

Key design parameters: - Compression ratio: 1.5:1 (low-oil seeds) to 2.5:1 (high-oil seeds like groundnut, sesame), Wormshaft speed: 45-60 rpm (high-oil seeds) to 110 rpm (low-oil seeds or high-capacity)

Cold pressing (Kachi Ghani): This uses no added heat. It preserves volatile aromatics, essential fatty acids, and natural antioxidants (tocopherols, lignans), which makes it more expensive even though it produces less oil.

5.3 Solvent Extraction

For maximum recovery (especially low-oil seeds like soybean), hexane (boiling point 68-69 degrees C) is the standard solvent.

Process:

1. Flaked seeds are steamed into porous pieces so the oil can be reached easily.

2. Heated hexane (61-62 degrees C) is sprayed over these pieces to dissolve and wash out the oil in continuous percolation extractor.

3. Miscella (oil-hexane mixture) is distilled; hexane is recovered (>95% recycling) for future use.

4. Residual meal enters Desolventizer-Toaster (DT) to clear out any leftover chemical traces and destroy harmful enzymes.

Efficiency: Residual oil in meal: 0.5-1.5%; aggregate oil recovery: >95%.

5.4 Edible Oil Refining (FSSAI Compliant)

Crude oil contains phospholipids, free fatty acids (FFA), pigments, and volatile compounds. Refining involves five unit operations:

Degumming: Hot water (71-80 degrees C) or phosphoric acid (1500-2500 ppm) removes hydratable and non-hydratable phospholipids via centrifugation.

Neutralization: Caustic soda (8-24% NaOH) saponifies FFAs into insoluble soapstock, removed by centrifugation. Oil is washed with hot water to remove trace soaps.

Bleaching: Activated bentonite/clay (0.5-2%) under vacuum (20-30 mm Hg) at 80-120 degrees C for 15-30 minutes removes pigments, peroxides, and trace metals. Filtered through hermetic leaf filters.

Deodorization: High-vacuum (1-5 mbar), high-temperature (210-250 degrees C) steam distillation strips volatile aldehydes, ketones, and FFA breakdown products, yielding bland, stable oil.

Winterization: For high-wax oils (sunflower, corn germ), slow cooling to 5-8 degrees C crystallizes waxes, which are filtered out using plate-and-frame presses, ensuring clarity at refrigeration temperatures.

Size reduction and flaking: Roller mills rupture cell walls and flakers flatten the material into thin layers (0.2-0.4 mm), maximizing surface-to-volume ratio for easy oil flow and solvent penetration.

Thermal conditioning (Cooking): Heating flakes at 105-130 degrees C for 30-120 minutes with an initial moisture level of 9-14.5%. This heating process works by clumping internal proteins, thinning the oil to reduce its thickness, and merging tiny oil droplets together.

6. Conclusion:

Farm mechanization and post-harvest technology are indispensable for transforming India's oilseed sector from subsistence-oriented to commercially competitive. Precision sowing with inclined plate planters establishes optimal crop geometry; post-harvest drying and hermetic storage preserves biochemical quality; spiral separators and AI-driven optical sorting ensure seed purity; and optimized screw pressing with FSSAI-compliant refining maximizes oil recovery while preserving nutritional integrity.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine

Volume 04, Spcl. Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-26

A DIGITAL AND MECHANICAL MAKEOVER FOR INDIA'S OILSEED VALUE CHAIN

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Introduction

Oilseed crops are central to Indian agriculture. It supports rural livelihoods, food security, nutrition and the agro-processing sector. Groundnut, soybean, rapeseed-mustard, sunflower, sesame, and safflower are the principal oilseed crops. In India, oilseed is cultivated approximately on 42.5 million hectares, producing around 41.5 million tonnes. Despite this, India faces a large gap between edible oil demand and domestic production. During 2023-24, the country's edible oil demand was at 25 million tonnes, while domestic production was only at 11.2 million tonnes. Imports were made to meet more than half of the requirement.

In India, due to small landholdings, labour shortages, traditional farming practices, and post harvest losses, oilseed crop productivity is low. Historically, bullock drawn tools and physical labor have been the mainstays of oilseed cultivation. Farm operations become delayed and ineffective as a result. The need for mechanization has grown due to low labor availability and growing labor expenses. While countries such as the USA, Western Europe, Russia, and Brazil have achieved mechanization levels of 75-95%, India's level remains around 40%. Farm mechanization can reduce labour and time requirement by 20-30% and save 15-20% of seed and fertilizer inputs and increase productivity by 10-15%. On the other hand, digital agriculture tools like precision farming, ICT based advisories, remote sensing, drones, and decision support systems, are enabling proper crop management and efficient resource use. Post harvest innovations are equally crucial for reducing losses and enhancing value addition. Improved harvesting, storage, processing and supply chain increases product quality, farmer income, and market competitiveness. Therefore, the transition from traditional farming to mechanized and digital agriculture offers a promising pathway for strengthening India's oilseed value chain.

2. Farm Mechanization

Agricultural mechanization plays an important role in modern crop production by ensuring operational efficiency, reducing labour and improving resource efficiency. Despite its importance, mechanization levels for major oilseed crops remain significantly lower (11.83-32.52%) compared to cereals. Land holdings in India are small and marginal. It requires appropriately designed tools and implements for crops. For tribal farmers in rainfed areas, introduction of small farm machinery increases production and quality of crop. Farmers find it difficult to purchase their own machinery due to high cost and low availability of suitable machinery. The government should focus on promoting mechanization specifically to increase reach to small and marginal farmers & regions where farm power availability is low.

3. Labour Saving Technologies for Small and Tribal Farmers

The adoption of labour-saving technologies is important in regions with labour shortages and migration issues. This is particularly true for farmers who depend heavily on family labour. These technologies play a crucial role in decreasing physical labour, improving operational efficiency and timely completion of farm activities.

The following technologies are suitable for small farmers and tribal farming systems.

3.1. Custom Hiring Centres (CHCs)

Custom Hiring Centres provide farm machinery and equipments on a rental basis, which enables farmers to access modern technologies without purchasing expensive machinery. Small and tribal farmers cannot afford tractors, seed drills, power weeders, or threshers due to low financial resources. CHCs bridge this gap by making mechanization services available at reasonable and affordable rates.

3.2. Women Friendly Farm Implements

Women have a significant share in oilseed cultivation, especially in sowing, weeding, harvesting, and post harvest activities. However, traditional tools require high physical effort and may lead to fatigue and health problems. Women friendly implements, as shown in figure 1, are lightweight and designed to reduce physical strain and improve work efficiency. These tools enhance labour productivity while promoting gender inclusive agricultural development.



Figure1. A woman farmer using cycle weeder



Figure 2. 1HP Phenix Solar Cultivator

3.3. Solar Powered Agricultural Equipment

Solar irrigation pumps and solar sprayers offer sustainable and cost effective alternatives to traditional fuel operated equipment. In many tribal and remote regions, access to electricity and fuel is limited. Solar powered devices, such as weeder, tiller, seeders, cultivator as in figure 2, reduce dependence on fossil fuels, lowers operating costs, and provide clean and green energy for farm activities. Their adoption contributes to environmental sustainability while improving the efficiency of farm operations.

3.4. Multipurpose Farm Machinery

Nowadays, machines are designed to perform several farm operations using a single machine. Equipment such as multipurpose power tillers can be used for land preparation, sowing, weeding, and transportation. It reduces the need for multiple implements, which lowers cost of investment and minimizes labour requirements. For small landholdings common in tribal areas, multipurpose machines offer an economical and practical solution.

3.5. Farmer Producer Organizations (FPOs) and Cooperative Mechanization

Farmer Producer Organizations and cooperative societies facilitate collective access to farm machinery. Through shared ownership, farmers can reduce individual investment costs and increase profits. This is particularly effective for tribal communities due to small landholdings and limited financial resources which restricts the adoption of mechanization technologies.

4. Smart Farming Technology in Oilseed Farming

It is changing the way oilseed crops like mustard, soybean, groundnut, and sunflower are grown in India. Instead of relying purely on traditional knowledge and manual labour, farmers are now using tools like sensors, drones, satellite imagery, and mobile apps to make better decisions from sowing to harvest.

4.1. Sensor Based Nutrient Management

The unremitting decline in mustard productivity and nutrient recovery is largely due to blanket fertilizer application and resulting nitrogen pollution. An advanced nutrient management tactic is the GreenSeeker (GS) optical sensor. It is developed on the four "R" principles (right source, right rate, right time, right place) has been widely used in field crops, but not evaluated in mustard. Crops like mustard, soybean, and sunflower have specific nutrient demands at critical stages like sulfur for mustard pod formation, boron for groundnut kernel filling, and zinc for soybean root development. Missing these windows costs yield. Sensors ensure nutrients reach the crop precisely when needed. Farmers using sensor-guided nutrient management report fertilizer savings of 15-25% while maintaining or improving yield. This results in a double gain of reduced input cost and better crop health.

4.2. Hyperspectral Imaging and Multispectral Imaging

Hyperspectral Imaging (HSI) technology provides incomparable capabilities for detection of physical, chemical, and biological properties of the samples. In agriculture, this technique is used for monitoring the agricultural farmland. The applications of the technique are of considerable importance for macronutrient analysis of plants including mapping of foliar nitrogen, detection of nitrogen deficiency, visualization of chemical distribution in leaves etc. For rapeseed and mustard farming, the technology has been found to be fairly useful for the detection of different pathogens and disease prognosticating, detection of pests and monitoring damages due to infestation, macronutrient analysis for monitoring fertilizer application, mapping of weeds population, prediction of seed yield, and determination of oilseed planting area.

For multispectral imaging, the Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) and the photosynthesis rate (Pn) are essential photosynthetic parameters for accurately estimating vegetation growth and productivity using multispectral vegetation indices (Vis). Despite their importance, few studies have compared the effectiveness of multispectral imagery and various machine learning techniques in estimating these photosynthetic traits under high vegetation coverage. Using unmanned aerial vehicle (UAV) based multispectral sensors, crop phenology and biotic stress conditions can be assessed using various spectral vegetation indices. The goal is to enhance the accuracy of predicting key agricultural parameters, such as leaf area index (LAI), soil and plant analyzer development (SPAD) chlorophyll, and yield.

4.3. Precision Sowing and Irrigation

Automated seed drills ensure uniform spacing and optimized seed rates. Drip or automated sprinkler irrigation systems, triggered by soil moisture sensors, prevent waterlogging, a condition to which mustard is particularly sensitive. Mustard sown on furrow-irrigated raised beds with precise row spacing and irrigated through drip in 12 small splits between 30-100 DAS increased seed yield and water-use efficiency compared to conventional flat sowing with check-basin irrigation.

4.4. Precision Breeding

Advanced molecular tools, including CRISPR-Cas9, provide unparalleled precision in genome editing, enabling targeted modifications for higher stress resilience and enhanced oil profiles. Much effort has been put into applying this technology to study specific genes and biosynthetic pathways, especially in species with many gene copies such as *B. napus*. Scientists have used CRISPR-Cas9 in the oilseed crop Camelina sativa (a model oilseed) to edit genes controlling ovule and seed development.

4.5. Drone

Drone technology in agriculture refers to the use of unmanned aerial vehicles, or UAVs, to collect data, inspect crops, and perform farming tasks from above. These drones are equipped with advanced sensors, cameras, GPS systems,

and sometimes spraying equipment. Their ability to capture real time information gives farmers a clear view of crop health, field conditions, and problem areas. Unlike traditional scouting methods, agricultural drones can cover large areas quickly and consistently. This makes them especially valuable for precision agriculture, where decisions are based on detailed field data rather than broad assumptions. A multirotor agri-drone is programmed with an RTK-GPS field map to broadcast-sow oilseed rape seed at a precise rate (about 3 kg/ha) in parallel flight lines, ensuring uniform stand without tractor tracks. Later, the same drone flies at low height over the crop to apply fungicide or pod-sealant at a fixed dose, giving even coverage, saving time and labour, and allowing operations even when the field is too wet for ground equipment.

4.6. Internet of Things

Internet of Things (IoT) system designed to revolutionize agricultural practices by providing real time monitoring of soil parameters, including temperature, moisture, salinity, EC, pH, nitrogen, potassium, and phosphorus levels. By integrating advanced IoT technologies, cloud computing, predictive algorithms, and a smart soil sensor, this system revolutionizes agriculture by enabling real time monitoring of critical factors. In a mustard field, the farmer installs soil-moisture and temperature sensors at root-zone depth and connects them to a small gateway that sends data to a mobile app. The app shows real-time moisture status and automatically switches on a drip irrigation pump when soil moisture falls below a set threshold and turns it off when the field reaches the optimum level.

4.7. Robotic Technology

Precision Planting and Seeding Autonomous Seeders: Robotic seed drills and rovers utilize GPS and computer vision to map out fields, digging and dropping seeds at optimal depths, spacing, and densities. Benefits in Oilseeds: Proper spacing and uniform depth are critical for oil rich crops to ensure maximum sunlight exposure and root expansion, which directly correlates to higher oil yield. On a rapeseed (canola) farm, a small autonomous field robot is programmed with GPS maps of the field and equipped with cameras and AI to recognize weeds between crop rows.

5. Oilseeds Kisaan Mitra

Oilseeds Kisaan Mitra is a 24×7, WhatsApp based, AI powered advisory service created to provide scientific, crop-wise guidance to oilseed farmers in India, including mustard and rapeseed growers. It has been developed by ICAR-Indian Institute of Oilseeds Research (ICAR-IIOR), Hyderabad, under the Indian Council of Agricultural Research (ICAR).

Oilseeds Kisaan Mitra is described as India's first nationwide WhatsApp AI advisory service exclusively for oilseed farmers (Fig.3). It functions as a chatbot that uses artificial intelligence to understand farmers' questions and respond with research-based recommendations drawn from ICAR and partner institutes' technical knowledge. The service operates round the clock (24x7) and is multilingual, meaning farmers can interact in any Indian language rather than only English or Hindi. It is designed to work directly within WhatsApp so that farmers do not have to install separate app or use a browser.



Figure3. Kisaan Oilseed Mitra Chatbot

The AI chatbot gives instant answers on broad range of farm decisions across the crop cycle:

- Variety/seed selection suitable for region, season and production conditions.

- Crop management practices such as sowing time, spacing, nutrient management and intercultural operations.
- Pest and disease control recommendations, including identification and management options.
- Irrigation advice depending on crop, growth stage and season.
- Post-harvest management to reduce losses and maintain quality (drying, storage).
- Information on seed availability and related inputs where such data is integrated.

For mustard/rapeseed, this can include guidance on optimal sowing windows, recommended varieties for a particular zone, fertilizer schedules (*e.g.,* N, P, S, micronutrients) and control of common diseases and insect pest.

6. Processing Technology

Advanced oilseed processing technologies are now beyond mechanical and solvent extraction methods. It includes assisted extraction techniques which improve oil yield and quality. Enzyme assisted extraction breaks down cell walls using enzyme for higher oil recovery with lower solvent consumption. Ultrasound assisted extraction uses ultrasonic waves that accelerates extraction while preserving oil quality. Microwave energy is used for rapid and energy efficient oil release from cells. Supercritical fluid extraction uses CO_2 at supercritical conditions to produce pure oil without solvent residues. It also eliminates health and environmental concerns associated with hexane.

Modern systems also include pressing with extrusion technology. It combines screw presses with feed extruders for maximum oil yields. It also provides a good press cake quality for feed applications. These advanced technologies shift focus from single processing steps to integrated production processes. It emphasizes on eco-friendly solvents (ethanol, supercritical CO_2, water enzymatic extraction), process intensification, and intelligent control systems that optimize parameters while lower energy costs. This ultimately enables oil producers to meet growing demands for higher quality and diverse vegetable oil products with improved production efficiency.

7. Value Addition in Oilseed Crops

Oilseeds are not just sources of oil. They generate significant value through it's byproducts. The oilseed processing industry produces:

- Hulls and shells: Used in animal feed and industrial applications
- Cakes and meals: High protein animal feed (soybean meal, rapeseed meal)
- Salad oils: Premium refined oils for culinary use
- Shortenings and margarine: Processed food ingredients
- Cooking oil: Various blended and fortified products.

The strategic approaches should be comprehensive infrastructure development, product diversification, and quality assurance. Processing and refining should be expanded to include modern facilities. This will increase oil recovery rates from traditional 85-90% to 95-98% through advanced solvent extraction and assisted extraction technologies. Development of fortified oil with added vitamins and nutrients, blended oils combining multiple oil types for optimal nutritional profiles should be made. Quality certification systems ensure that exported value added products meet international standards. Efficient supply of oilseed product will increase its reach to all parts of the country. Public awareness will educate consumers on

dietary guidelines and oil quality. This will create a demand for high-quality value-added products.

With proper implementation of post harvest management, advanced processing technologies, and value addition strategies:

- Post harvest losses can be reduced from 6% to <2%.
- Oil recovery rates can increase from 85-90% to 95-98%.
- Domestic oil availability can increase by 1.5-2 million tonnes annually.
- Value addition can increase farmer income by 20-30% through locally processed products.

8. Conclusion

The transformation of India's oilseed sector from traditional farming to mechanized and digital agriculture is essential for improving productivity, profitability, and self-reliance in edible oil production. Crop-specific machinery, labour saving technologies and smart farming tools can significantly reduce production losses. Increasing access of machines, to small and tribal farmers, will improve resource-use efficiency, farmer income and oil recovery rates. Promotion of precision farming and value addition in oilseed will be beneficial in long term. Agriculture technologies like sensors, drones, IoT-based monitoring systems, and AI chatbots, can support data-driven decision-making and sustainable resource management. Investment in rural infrastructure, digital connectivity, farmer training, and research-driven innovations will be crucial for large-scale adoption of these technologies. Innovations in processing, storage, and value addition can substantially reduce post-harvest losses, improve oil recovery rates, and generate additional income opportunities through diversified oilseed products and by-products. A coordinated approach which integrates technology, infrastructure and farmer-centric support systems can help build a resilient and sustainable oilseed value chain. This will reduce India's dependence on edible oil imports while ensuring long-term agricultural growth.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine

Volume 04, Spcl. Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-27

EMPOWERING WOMEN: THE MAJOR ROLE IN OILSEED FARMING AND TRIBAL LIVELIHOOD SECURITY

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Abstract

Oilseed crops are important in improving livelihoods of tribal people through income, employment and nutritional security. Tribal women are key contributors across the oilseed value chain, participating in cultivation, harvesting, processing, value addition, and marketing activities. Women have been taking part in small-scale oil extraction and entrepreneurship through Self-Help Groups (SHGs) and government-sponsored schemes, which have led to new sources of income. They add to household food security, economic resilience and community development. Access to technology, training, credit and markets can further enhance women's participation and ensure sustainable livelihood security in tribal regions.

Introduction

Agriculture is fundamental to the Indian economy and provides the main source of income for many people. India ranks among the top agricultural producers globally, with millions relying on crop farming, livestock, forestry, and related sectors. Women make up a significant part of the agricultural workforce. They are vital in tasks like sowing, transplanting, weeding, harvesting, and managing post-harvest activities. Despite their important contributions, women often encounter issues such as pay gaps, limited access to resources, and a lack of acknowledgment for their role in agriculture.

Among different agricultural sectors, oilseed farming has great potential to improve rural livelihoods. Crops like groundnut, mustard, sesame, niger, soybean, and sunflower are key sources of income, nutrition, and jobs. In addition to providing cooking oil, oilseed crops produce valuable by-products like oilcakes, which can be used as animal feed and in various industrial and household uses. Growing, processing, and marketing oilseeds create job opportunities throughout the value chain.

Livelihood security includes the food, nutrition, and financial stability needed for a healthy and respectful life. While India has made notable strides in food grain production, problems like poverty, unemployment, and uneven access to resources still impact rural families. To strengthen livelihood security for farming communities, it is crucial to boost agricultural productivity and encourage profitable crops.

In the tribal-dominated areas of Odisha, especially the KBK districts, oilseed farming can play a major role in generating income, creating jobs, and building economic resilience. Increasing production, adding value, and developing market connections for oilseed crops can enhance household livelihoods, empower women, and support sustainable rural development.

Ethnobotanical significance

Ethnobotany refers to the study of how people of a particular culture and region make use of indigenous plants. This has a significance because indigenous uses when given a broader use perspective can help farmers in rural areas generate revenues apart from main use product. Not only by commercial oilseeds but also by integrating tree-borne oilseeds such as Neem, Mahua etc. This can help them tackle financial issues to a certain extent that too in a sustainable way where nothing goes to waste.

Usually, people in tribal and rural areas are not as educated as compared to people who have already been exposed to this side of production to conversion.



Plant part used for extraction of oil (a: Seed powder of *Azadirachta indica* A. Juss., b: Seed of *Sesamum indicum* L., c: Seed of *Arachis hypogaea* L., d: Fruit of *Ricinus communis* L., e: Fruit of *Madhuca longifolia* (L.) J.F. Macbr., f: Seed of *Schleichera oleosa* (Lour.) Oken, g: Seed of *Azadirachta indica* A. Juss., h: Dried seed of *Ricinus communis* L

Role of women in oilseed value chain and livelihood security

Women are the backbone of oilseed-based livelihoods in rural and tribal regions, contributing significantly to cultivation, processing, and marketing activities. Their participation not only supports household income but also strengthens livelihood security and food systems.

Cultivation

Women perform nearly 60-80% of manual operations in oilseed cultivation. They are actively involved in seed selection, sowing, gap filling, weeding, intercultural operations, harvesting, and post-harvest handling. In crops such as groundnut, sesame, mustard, and niger, women undertake labor-intensive and precision-based tasks that directly influence productivity.

The growing phenomenon of the "feminization of agriculture" has further increased women's responsibilities. With many men migrating to urban areas for employment, women increasingly manage farms, make production decisions, and sustain agricultural activities, particularly in tribal and rainfed regions.

Processing and Value Addition

Women play a dominant role in post-harvest management of oilseeds. Their responsibilities include drying, cleaning, grading, shelling, and safe storage of produce. These activities help reduce losses and improve product quality.

Through Self-Help Groups (SHGs) and livelihood missions, women are increasingly involved in value addition activities such as operating small-scale oil extraction units, producing cold-pressed edible oils, preparing oilseed-based food products, and marketing processed goods. Such enterprises generate additional income and employment opportunities at the village level.

Marketing

Women frequently participate in local marketing systems by selling oilseeds and value-added products in village markets and weekly haats. Income earned from these activities contributes directly to household food security, education, and healthcare expenses. However, women's participation in larger and formal markets remains limited. Social barriers, restricted mobility, inadequate market information, and limited access to transportation often prevent them from engaging effectively in wholesale trade and regulated agricultural markets. Strengthening women-led Farmer Producer Organizations (FPOs), cooperatives, and market linkages can help overcome these challenges and enhance their economic empowerment.

Tribal livelihood security by integrating oilseeds byproducts

In tribal districts such as Mayurbhanj, Koraput, Rayagada, Kandhamal, Nabarangpur and Malkangiri, oil-yielding plants provide food, medicine, fuel and income. The rich indigenous

knowledge about oil extraction and utilization, emapahsing the livelihood support, cultural practices and sustainable resource management.

Integration of oilseeds include:

Groundnut - Oil is used for household consumption and sale. Groundnut cake as protein-rich cattle feed and shells used for composting and mushroom cultivation. Also used as a baking ingredient as kernels and groundnut spread.

Sesame - Oil is used for cooking and cultural rituals, cakes applied as organic manure and potential for value-added products through SHGs.

Mustard - Oil is used for food and traditional medicinal uses and oilcakes as organic fertilizer and bio-pesticide. It has potential opportunities in small processing units. It is also used as spices, preparation of mustard sauce used in various delicacies.

Mahua (*Madhuca longifolia*) - Tribal women collect seeds from forests and oil used for skin care, medicinal purposes and local markets.It has high livelihood significance among forest-dependent households.

Neem and Karanja - Oils used in organic agriculture and pest management and has scope for bio- pesticide entripise that can be led by women's groups. Seeds collected are from community lands and forests. Scope for bio-pesticide enterprises led by women's groups.

Niger - Seeds contain approximately 35-45% edible oil. Oil is used for cooking, medicinal purposes, and traditional healthcare practices and provides a valuable source of household income in tribal regions.

Cold-Pressed Oil Production - Oil is extracted mechanically without the application of high heat or chemical solvents, which retains natural nutrients, antioxidants, vitamins, and flavour compounds and produces premium-quality edible oils with higher market value. This generates additional income through value addition at the village level and can be established as a small-scale enterprise by SHGs, FPOs, and rural entrepreneurs which creates local employment opportunities in processing, packaging, and marketing. This supports consumer demand for natural and healthy food products and reduce dependency on large processing unit.

Oilcakes for livestock: Oilcake is the nutrient-rich residue left after oil extraction. It contains high levels of protein, carbohydrates, minerals, and energy and is used as a supplementary feed for cattle, buffaloes, goats, sheep, and poultry. Improves animal growth, milk production, and overall health which reduces expenditure on commercial livestock feed. This shows enhanced integration between crop production and livestock farming systems. And generates additional value from oilseed processing, ensuring minimal waste. Some commonly used oilcakes include groundnut cake, mustard cake, sesame cake, sunflower cake, and Niger cake.

Livelihood security is promoted by:

Increase income and employment: By producing value added products and create employment opportunities beyond crop cultivation.

Nutritional security: Enhances nutritional security through edible oil production and support livestock-based livelihood by providing quality feed.

Economic security: Strengthens the economic resilience of tribal and smallholder farming households by providing year-long employment opportunities and local enterprise development.

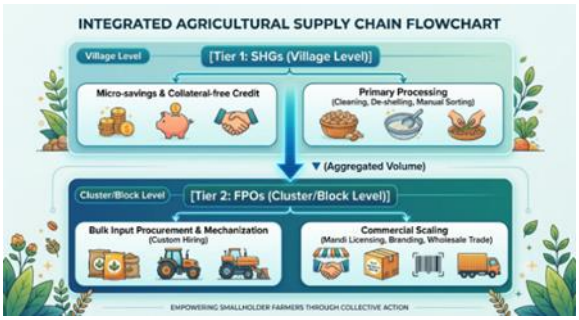
Social security: By inclusion of community institutions, women and marginalized groups.

Promotion of Livelihood Security Approaches:

Livelihood security in agriculture could be ensured through approaches such as crop diversification, sustainable agriculture, and the use of advanced technology to boost production and minimize risk factors. Value addition, agro-

processing, and marketing of the produce help to earn more profits from agricultural activities. Community organizations like FPOs, cooperatives, and SHGs increase collaboration and access to resources. Adoption of climate-smart agriculture and efficient management of resources along with inclusive gender participation adds up to the resilience and household welfare. Moreover, supportive policies, provision of credit, insurance schemes, and skill enhancement opportunities offer prospects of sustainable livelihood security in agriculture.

Role of SHGs and FPOs for economic development and women empowerment



Self-help Groups (SHGs): Promoting from the grassroot

Collateral-Free Credit Links: Because women rarely hold titles to agricultural land, they are routinely locked out of institutional bank loans. SHGs pool small savings to create an independent corpus fund, providing members with hassle-free, collateral-free credit at reasonable internal interest rates. This helps them get quality seed of groundnut, mustard, sesame, soyabean, sunflower etc which solves futher hassle of decreased profits by more investment in inputs.

Decentralizing Post-Harvest Operations: SHGs provide the organizational structure required for primary value addition. Instead of individual women spending hours manually de-shelling or winnowing oilseeds in isolation, SHG collectives pool labor and establish village-level aggregation points.

Case of Mission Shakti:

The program launched by Government of Odisha in 2015, has strengthened the involvement of women in oilseed production by helping them access credit opportunities and bank linkages for agricultural and agro-processing activities. Support women-led micro-enterprises involved in oil extraction, packaging, and marketing of edible oils. Promotes value addition through small-scale processing units producing cold-pressed oils and other oilseed-based products and strengthens collective marketing by improving bargaining power. Help in capacity building and skill development along with it provide social and economic inclusion.



Farmer Producer Organizations (FPOs): Scaling up Market Power

SHGs excel at financial pooling and village-level production, but they often lack the commercial scale to engage in competitive wholesale trade. This is where FPOs-registered as legal corporate entities owned entirely by smallholders-step in to bridge the gap.

Economies of scale and input access:

- FPOs aggregate the crop volume generated by hundreds of individual SHG clusters. By purchasing inputs in bulk (such as bio-fertilizers, high-yielding hybrid seeds, or crop insurance products), the FPO slashes production costs for its female members.
- **Value- addition and processing:** FPOs collectively provide resources for value addition and production of byproducts

such a bakery ingredient, seed kernel cakes etc.

- Overcoming the "Mandi Barrier".
- An all-women FPO can secure a collective mandi trading license, enabling women to bypass local village brokers entirely. They sell directly to state procurement agencies, large agri-businesses, or consumer brands at higher minimum support prices (MSPs).

Strengthening oilseed-based value chains by policy support and government initiatives:

NMEO-Oil Palm (2021) Supports expanding oil palm cultivations and enhancing edible oil availability in the country. Aims to enhance employment, attract investment, decrease imports and boost income generation among farmers. NMEO-Oilseeds (2024) Aids to achieve increased productivity, quality seeds access, increased processing and stronger market linkages for enhancing traditional oil seeds' value chains.

Krishi Sakhi Deliver last-mile agricultural advisory and extension support through specially trained rural women. Also promotes sustainable agricultural practices, and farm produce collection and marketing.

PM-AASHA Procurement of oil seeds by different agencies including NAFED and NCCF at MSP for safeguarding farmers against price crash and distress sale. NFSM-Oilseeds Encourages distribution of quality seeds, planting materials, and also provides training and demonstrations of modern agriculture techniques for the farmers.

Minimum Support Price (MSP) MSP has been declared for different oilseeds such as groundnut, mustard, sesamum, sunflower and soybean to offer protection against risks of market fluctuation and price risk to the farmers.

Kisan Credit Card (KCC) Availability of credit to farmers at affordable rates and in time for farming expenses, such as buying necessary inputs. Also reduces dependency of farmers on non-institutional money lenders for financing farm operations. Pradhan Mantri Janjatiya Vikas Mission (PMJVM) Undertakes a wide range of activities such as skill development, value addition to forest products, entrepreneurship development and market access to enhance tribal livelihood in a sustainable manner.

Van Dhan Vikas Yojana (VDVY) Aims to value addition and market access for forest and other minor agricultural produce through tribal collectives. These collectives can establish small and medium-scale enterprises for processing forest and other agricultural produces. Tribal Sub-Plan

(TSP) Financial provision of infrastructure development, credit availability, employment generation for enhancing production, including crop production.

Agriculture Production Cluster (APC) Model (Odisha) Develops agricultural produce clusters with focus on synchronized production and supply chains among tribal women on oil seeds likeniger and sesame.

Future prospects along with sustainable livelihood security:

Climate Resilience: Adoption of drought-tolerant oilseed varieties and crop rotation helps tribal farmers cope with climate uncertainties. It improves soil health and provides more stable incomes during monsoon-dependent farming seasons.

Decentralized Value Addition: Village-level oil processing units enable local production and utilization of by-products such as oilcakes for livestock feed. These enterprises create income opportunities, especially for women-led groups.

Institutional and Digital Scaling: Linking tribal farmers and SHGs with FPOs and producer companies strengthens market access and improves price realization. Digital platforms like eNAM help reduce dependence on intermediaries.

Ethnobotanical Commercialization: Value addition to traditional forest-based oils such as

Mahua and Kusum creates additional income during lean periods. Branding and processing can help access premium cosmetic and niche markets.

Policy and Government Convergence: Support from schemes such as National Mission on Edible Oils – Oil Palm and Van Dhan Yojana can strengthen infrastructure, finance, and market support. This helps transform traditional tribal oilseed farming into a sustainable agribusiness model.

Conclusion

The oilseeds constitute a large proportion of agriculture but due to lack of knowledge about how it can bring more cash generation with some mere changes and adaptation of practices it has been neglected or it can be said overlooked upon. As women are a major representative in the field of Agriculture although the work is continuously unnoticed should be taken into consideration and they must be provided opportunities of education, exposure, export facilities so that they could gain financial stability. Now on the livelihood security of the whole tribal community the use of indigenous knowledge and also teaching them the income generation by use of by-products, value chain can be strengthened, ensuring equitable benefits for local producers while contributing to sustainable development goals. Through knowledge sharing platforms, capacity-building initiatives, and the establishment of market linkages, stakeholders can enhance the sustainability and profitability of oil seed production of both edible and TBO oil seed production. The overall security of tribals in oilseed agriculture can be ensured by various government policy, SHGs and FPOs.

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Go Green, Learn Green
An Agricultural Monthly e-Magazine

Volume 04, Spcl. Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-28

DRIVING SOCIO-ECONOMIC TRANSFORMATION THROUGH OILSEED TECHNOLOGIES IN THE TRIBAL REGIONS OF KORAPUT DISTRICT

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Abstract

Indigenous women in the tribal villages of Koraput, Odisha are moving from being the primary collectors of tree-borne oilseeds to becoming market leaders. Odisha is blessed with abundant availability of tree borne oilseeds but their potential is yet to be fully tapped. The seeds give natural oils for all sorts of things from medicine and skin care to cooking fuels and food ingredients. There are many challenges from the system like low pricing and lack of access to the market etc. Women began using new oilseeds technologies such as climate resilient farming, digital advisory, post-harvest processing and Small Farmers Large Field (SFLF) Model. Market innovations like the Small Farmer Large Field model, Farmer Producer Organizations (fpos) and TRIFED's Marketing Platform are leading the way on this effort and linking the old ways of farming with new ways. The new value chain is sustainable and helps support women, increase household incomes and develop the community while protecting the forests. This is a revolution in Koraput, not just of oilseeds, but of sustainable, equitable and empowering economic systems that honour traditional wisdom and embrace modern innovation, with women at the centre of development.

Keywords: Women, Tree-borne oilseed, Technology Interventions, Market Innovation, Sustainable Value Chain.

Introduction

In the distant tribal hamlets of Odisha's Koraput district a quiet revolution is taking place. Generations have collected seeds like Sal, Kusum, Karanj, Mahua, and Castor from forest trees, but most families only saw these as a basic resource never a real chance for economic growth. Right now, that mindset's turning upside down. Instead of just surviving, women in these tribal communities are stepping up as innovators and change-makers, using new oilseed technologies to improve their own lives. This isn't just about earning a bit more. It's about empowerment, sustainable farming, and breaking the cycle of poverty for thousand. Koraput district, spread over 14 blocks, with a predominantly tribal population, is a unique opportunity to blend the wisdom of the traditional with the technical of the modern. The majority of primary seed collectors in the area are women, but they have long faced systemic challenges, including poor access to markets, a lack of processing tools, and limited financial literacy.

The Current Reality: Untapped Potential and Systemic Challenges

Odisha's forests offer up plenty of tree-borne oilseeds, but much of that value slips away before ever reaching the collectors' hands. Oil from these seeds can do a lot heal, cook, fuel, even nurture skin yet, for the tribal women

collecting them, prices are often so low that it barely seems worth the effort.

Oil mills in this region usually run below capacity because there's no steady, reliable seed supply.a vicious cycle that hurts both gatherers and processors. NABARD's study in Koraput shows these seeds are crucial for both food and a little income, especially the varieties Sal, Kusum, Karanj, and Mahua. But so much potential is still out there, waiting to be unlocked.

The obstacles facing women collectors are complex and interconnected:

Low prices ,Collection becomes economically unfeasible, Lack of market access , Makes women vulnerable to exploitation by traders , No processing capacity , Prevents them from adding value to raw seeds ,Financial illiteracy ,Limits their ability to negotiate fair prices ,Remote villages ,High transport costs eat into meager profits, Fragmented land holdings, Reduces their collective bargaining power.These hurdles have historically left tribal women vulnerable to exploitation, preventing them from seeing the true rewards of their hard work and deep ecological knowledge.

Women as Catalysts: The Gender Dimension of Oilseed Innovation

Collection of oilseeds in Koraput has a deep gender dimension. Women would be the first to benefit from the full utilization of these forest resources. The truth is that oilseed development is not just an agricultural project, it is a key strategy for women's empowerment. Already, tribal women in Koraput have shown extraordinary resilience and leadership in managing supply chains. Women have managed the logistics of getting seeds from remote villages to company warehouses by public transport, and overseen quality control and coordination across district lines in a number of initiatives. This proves that they have the full ability to deal with the complex business operations when provided with the right training and support.

Technology Interventions: Bridging Tradition and Innovation

1. Storage and Seed Quality Technologies

Fresh, reliable seeds set the stage for better harvests. Tribal communities get involved in seed production, keeping the process local and trusted. Modern storage steps is to prevent spoilage, so seeds keep their quality and value, nutrition and profit stay intact. The state or cooperative groups-especially women's self-help groups set up seed gardens to guarantee a steady flow of top-tier seeds for everyone.

2. Equipment for Post-Harvest Processing

Good infrastructure completely changes the story. Certain crops, like oil palm, need to be processed quickly within a day or the quality drops. Local processing equipment becomes a lifeline. NGOs step in, helping communities acquire small-scale tools for handling cereals and oilseeds. Women lead the way with village processing units, taking raw seeds and turning them into products ready for the market. This doesn't just add value; it brings in a lot more income.

3. Climate-Resilient Farming Practices

When farmers switch to climate-smart methods, they're able to get higher prices instead of being forced to sell everything after harvest at low rates. These new farming technologies especially for oilseeds- keep production steady, even as weather patterns become more unpredictable.

4. Digital Advisory Systems

Farmers get real help right on their phones. Voice and text updates in local languages give them clear, useful tips to boost their crop yields. Educational videos in regional languages break down essential methods in a way farmers can actually see and understand. Over 3 lakh texts have already reached thousands of oilseed farmers through a simple SMS portal.

5. Small Farmers Large Field (SFLF) Model

Small land plots make farming tough. To fix that, the Small Farmers Large Field Model from TAFSSA brings people together combining scattered fields into one bigger stretch. The pilot in 2023 brought 54 small farmers together to share better seeds, on-time delivery, good information, and easier connections to markets. Working together, they get stronger yields and more bargaining power.

Market Innovation: Creating Sustainable Value Chains

Technology is not the only solution; market innovation plays an equally important role in socio-economic transformation. The use of Public Private Partnerships (PPPs) in marketing has greatly alleviated the burden on farmers. There have been many market integration practices that are proving to be successful in Koraput and its vicinity.

1. Farmers Producer Organizations (FPOs)

By associating with FPOs, farmers can develop greater negotiating powers to fetch higher prices for their quality produce. These organizations provide the institutional framework for marketing, value addition to the produce, and development of new products. An FPO has already succeeded in linking tribal women farmers to the market in Koraput.

2. Marketing Platform of TRIFED

TRIFED is an agency that tries to take products of the tribal community to national and international audiences. As a facilitator, TRIFED provides the tribes with the information, tools, and know-how that they need to carry out systematic operations. Their presence covers the following areas: a chain of 'Tribes India' stores in the country, an e-commerce website at market.tribesindia.com, partnerships with platforms like Amazon, Flipkart, Snapdeal, Myntra, and other players, and the successful launching of products in the US and Europe. TRIFED also helps the tribal women artisans and entrepreneurs by providing them with a platform for displaying their creativity.

3. Local Haats and "Vegetables on Wheels"

A few of the methods that have proven effective in addressing marketing crises include "Vegetables on Wheels", selling to local traders or ORMAS, and revitalizing local haats. These methods reduce costs associated with transport and give women collectors a direct access to the market.

4. Rice Fallow Management for Oilseeds

The Department of Agriculture and Farmers' Empowerment in Odisha rolled out the "Comprehensive Project on Rice Fallow Management (CRFM)" for the 2023-24 Rabi season. They want to make the most of the land left idle after rice harvests by bringing those fallow fields under pulses and oilseeds. To help farmers get the best results, the program supplies quality seeds, bio-fertilizers, micronutrients, weed control products, and pest management materials.

5. National Mission on Edible Oils-Oilseeds (NMEO-OS)

The Government of India is running the NMEO-OS and NMEO-OP missions to make the country self-sufficient in oilseeds. The goal is pretty ambitious—produce around 70 million tonnes of oilseeds by 2030-31. These efforts aren't just about numbers; they push for higher yields, better crop varieties, more involvement from the private sector, and smooth procurement systems for farmers. From 2014 to 2024, land under oilseeds went up by more than 18%, production climbed by almost 55%, and per-hectare yields rose about 31%.

Socio-Economic Impact: Measuring Transformation

The shift toward oilseed technologies in the tribal regions of Kora put is creating a multi-dimensional socio-economic transformation:

- Income Enhancement: When the potential of tree-borne oilseeds is fully realized, it directly increases the income of tribal collectors, most of whom are women. With better pricing and support from NGOs and the government, farmers no longer feel forced to sell their produce at low rates immediately after harvest.
- Forest Conservation: A thriving oilseed industry gives local communities a reason to protect and manage their forests sustainably. This creates a healthy cycle where economic growth actually supports environmental conservation and climate resilience.
- Nutritional Security: By linking agricultural production to food security, communities are seeing improved nutrition. As oilseeds become more widely available, they provide essential nutrients that strengthen the health of the community.
- Educational Progress: The district administration is working hard to lift thousands of families out of poverty, fight illiteracy particularly among scheduled tribes and improve female literacy rates. The financial stability gained from oilseed income allows families to finally invest in their children's education.
- Health Improvements: Economic empowerment leads directly to better community health, notably through reduced infant mortality rates (IMR) and lower malnutrition levels. This progress is driven by improved access to healthcare and better nutrition resulting from increased oilseed consumption.
- Women's Leadership: Raimati Ghiuria, a 36-year-old from the Bhumia community in Koraput, has emerged as a powerful symbol of resilience and leadership. Her journey shows how entrepreneurship in agriculture and oilseeds can empower tribal women to step up as leaders within their own communities.

Conclusion

The way Koraput's tribal regions are being transformed through oilseed technologies serves as a powerful blueprint for socio-economic growth. It is a model that successfully blends women's empowerment, market innovation, and technological progress. Through their resilience and leadership, the tribal women of Koraput are demonstrating that oilseed technologies can trigger profound socio-economic shifts.

As Raimati Ghiuria's journey shows, when women are given access to the right seeds, technology, and markets, entire food systems begin to evolve. This revolution in Koraput isn't just about oilseeds; it's about building sustainable, fair, and empowering economic systems, systems that respect traditional wisdom while embracing modern innovation, all while keeping women at the heart of development.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine

Volume 04, Spcl. Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-29

SEEDS OF RESILIENCE: HOW TRIBAL HILL FARMERS ARE RECLAIMING THEIR OILSEED HERITAGE IN A CHANGING CLIMATE

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Introduction

Climate change is reshaping agriculture across the world, but nowhere are its impacts felt more profoundly than in India's tribal hill regions. These landscapes, characterized by steep slopes, fragile soils, and rainfed farming, support millions of tribal households whose livelihoods depend on agriculture. Despite limited resources, these communities have sustained diverse oilseed crops such as sesame, niger, linseed, mustard, and safflower for generations through indigenous knowledge, locally adapted farming practices, and careful stewardship of natural resources.

Imagine walking through a mist-covered hillside at sunrise. Terraced fields stretch across the slopes, where sesame flowers sway gently in the morning breeze. A tribal woman carefully inspects the crop, drawing upon decades of farming experience inherited from her family. She understands subtle changes in soil moisture, rainfall patterns, and plant growth without relying on sophisticated instruments. For generations, such knowledge has helped tribal communities cultivate crops under challenging conditions.

Today, however, this traditional wisdom is being tested by increasingly erratic weather. Delayed monsoons, prolonged dry spells, rising temperatures, and frequent extreme rainfall events are making agriculture more uncertain than ever before. At the same time, migration, shrinking farm sizes, declining soil fertility, and changing market conditions further threaten the sustainability of tribal farming systems.

Among the crops cultivated in these regions, oilseeds occupy a special place. Besides contributing to household nutrition and income, they are deeply intertwined with local food traditions, festivals, medicinal practices, and cultural identity. Building climate resilience in tribal hill agriculture therefore requires combining indigenous knowledge with modern scientific innovations and effective agricultural extension services.

"When the rains failed, my sesame survived because I followed the methods my grandmother taught me. The hill itself has always been our teacher" — Tribal woman farmer, Koraput, Odisha

Understanding Tribal Hill Agro-Ecosystems

Tribal hill agro-ecosystems differ significantly from conventional agricultural landscapes. Their steep topography, highly variable rainfall, shallow lateritic soils, and limited irrigation make farming inherently challenging. These fragile ecosystems are particularly vulnerable to soil erosion, nutrient depletion, and moisture stress, reducing agricultural productivity

and increasing production risks (Sharda *et al.*, 2007).

Agriculture in these regions is closely integrated with forests, livestock, and local biodiversity. Farmers cultivate multiple crops simultaneously, diversify production, and rely heavily on locally available resources to reduce production risks. Traditional farming practices have evolved over centuries to suit the unique ecological conditions of these landscapes.

Women play a central role in sustaining these farming systems. They are responsible for seed selection, storage, sowing, weeding, harvesting, and preserving indigenous crop varieties. Knowledge is passed orally across generations, allowing communities to adapt continuously to changing environmental conditions (Patel & Mishra, 2019).

Unlike commercial agriculture, tribal farmers often prioritize livelihood security over maximizing production. Their farming decisions emphasize stability, risk reduction, and conservation of natural resources rather than short-term economic gains.

Oilseed Diversity in Tribal Hill Regions

Oilseeds have supported tribal livelihoods for centuries by providing edible oils, nutritional security, livestock feed, medicinal products, and household income.

Each crop possesses unique characteristics that enable it to thrive under specific hill conditions while fulfilling distinct cultural and economic roles.

Crop	Key Hill-Adapted Traits	Cultural / Nutritional Role	Major Climate Challenge
Sesame (*Sesamum indicum*)	Drought tolerant; matures within 70–90 days; performs well on poor lateritic soils	Used in cooking, religious ceremonies, festivals, and local markets	Terminal drought and pod shattering during harvest
Niger (*Guizotia abyssinica*)	Tolerant to waterlogging, acidic soils, and several pests	Traditional edible oil; bird feed; important tribal cash crop	Low harvest index and poor threshability
Linseed (*Linum usitatissimum*)	Cool-season crop suitable for higher elevations; frost tolerant	Rich source of omega-3 fatty acids; medicinal and fibre uses	Susceptibility to rust disease and limited improved varieties
Mustard (*Brassica* spp.)	Cold tolerant with flexible sowing period	Cooking oil, leafy vegetables, and commercial market demand	Aphid infestation and *Alternaria* disease under humid conditions

Safflower (***Carthamus tinctorius***)	Deep rooting system with excellent drought tolerance	Edible oil, medicinal uses, and natural dye	Low market profitability due to competition from cheaper edible oils

These crops are far more than agricultural commodities. Sesame is integral to religious rituals and festive foods, while niger oil remains an important part of traditional diets in several tribal communities. Such cultural significance often influences farmers' decisions as much as productivity or market returns. Therefore, successful climate adaptation strategies must respect and build upon these local traditions rather than replacing them with uniform technological solutions.

Climate Change Challenges and Climate-Smart Pathways for Tribal Hill Oilseed Farming

Climate change has emerged as one of the greatest threats to sustainable agriculture in India's tribal hill regions. Unlike sudden natural disasters, climate change affects farming gradually through delayed monsoons, prolonged dry spells, rising temperatures, erratic rainfall, and increasing pest and disease outbreaks. These interconnected stresses reduce crop productivity, threaten household food security, and increase the vulnerability of farming communities (Krishnan & Swain, 2017).

Oilseed crops are particularly sensitive to climatic variability. Sesame, for example, requires adequate soil moisture during flowering and pod development. Even a short dry spell during this critical stage can substantially reduce yield (Reddy & Bhatt, 2010). Similarly, heavy rainfall during maturity increases pod shattering and harvest losses. In higher altitudes, warmer winters have altered the flowering period of crops such as linseed, increasing their exposure to frost damage and reducing seed production (Krishnan & Swain, 2017). Continuous soil erosion, declining organic matter, and reduced water-holding capacity further aggravate moisture stress, making crop production increasingly uncertain (Sharda et al., 2007).

Despite these challenges, tribal communities possess a remarkable capacity to adapt. Their farming systems have evolved through generations of experimentation and observation, producing locally adapted crop varieties and resource-conserving management practices. These indigenous innovations provide an important foundation for building climate-resilient agriculture.

One of the greatest strengths of tribal agriculture lies in its rich diversity of indigenous oilseed landraces. Traditional varieties of sesame, niger, and linseed have evolved under local environmental conditions over centuries and often possess natural tolerance to drought, acidic soils, waterlogging, and certain pests and diseases (Upadhyaya et al., 2011). Conserving these valuable genetic resources through community seed banks not only safeguards agricultural biodiversity but also provides future breeding programmes with important sources of climate-resilient traits (Bioversity International, 2017).

Climate resilience can be further strengthened through simple, low-cost agronomic interventions that are well suited to resource-poor farming systems. Seed treatment with bio-agents, seed priming before sowing, timely planting based on rainfall forecasts, mixed cropping, intercropping, organic nutrient

management, contour cultivation, mulching, and rainwater harvesting all contribute to improving soil moisture conservation and reducing production risks. Intercropping sesame with red gram, for instance, enhances resource use efficiency while providing greater yield stability under variable climatic conditions (Ghosh, 2004). Likewise, incorporating farmyard manure, green manures, and beneficial microorganisms improves soil fertility, enhances microbial activity, and increases the soil's capacity to retain moisture (Tilak et al., 2005).

Agricultural extension plays an equally important role in supporting climate adaptation. Rather than promoting uniform recommendations, extension systems must recognize and build upon farmers' existing knowledge and local innovations. Participatory approaches, such as Participatory Varietal Selection (PVS), allow farmers to evaluate improved varieties under their own field conditions and select those that best match local environments and preferences (Witcombe et al., 1996). Such collaborative approaches strengthen farmers' confidence, improve technology adoption, and encourage continuous learning between researchers, extension personnel, and farming communities.

Women deserve particular attention in climate adaptation strategies. As primary custodians of indigenous seed systems and household food security, they play a central role in conserving biodiversity and managing crop production. Empowering women through training, farmer groups, self-help organizations, and leadership in community seed banks can significantly enhance the effectiveness of extension programmes (Patel & Mishra, 2019).

Digital technologies also present new opportunities for strengthening extension services in remote tribal regions. Mobile-based advisories, weather forecasts, WhatsApp farmer groups, community radio, and locally trained extension volunteers can improve farmers' access to timely information on weather, pest management, improved production practices, and market opportunities. However, digital tools should complement—not replace—the trusted relationships between farmers, extension professionals, Krishi Vigyan Kendras (KVKs), and progressive local farmers (Meera et al., 2004).

Climate resilience also depends on creating supportive market and policy environments. Improving access to quality seed, strengthening procurement mechanisms, promoting value addition, encouraging community-based processing, and developing niche markets for traditional tribal oilseed products can significantly improve farm profitability. Premium products such as cold-pressed sesame and niger oil, marketed through geographical indication (GI) tags or tribal branding initiatives, offer promising opportunities to enhance rural incomes while preserving traditional farming systems.

Ultimately, strengthening climate resilience in tribal hill agriculture requires an integrated approach that combines indigenous knowledge, scientific research, climate-smart agronomic practices, participatory extension, and supportive public policies. Such a holistic strategy not only enhances oilseed productivity but also conserves biodiversity, strengthens livelihoods, and preserves the rich cultural heritage of India's tribal farming communities.

The Road Ahead

Tribal hill farmers have demonstrated remarkable resilience by sustaining diverse oilseed production systems under challenging environmental conditions for generations. Their farming practices, rooted in indigenous knowledge and close interaction with nature, offer valuable lessons for building climate-resilient agriculture. However, the increasing frequency of climatic extremes demands stronger collaboration between farmers, researchers, extension professionals, and policymakers to safeguard these fragile agro-ecosystems.

Future efforts should focus on conserving indigenous oilseed germplasm through community seed banks, promoting climate-smart agronomic practices, strengthening participatory research and extension, and improving farmers' access to quality inputs, timely advisory services, and remunerative markets. Women, who are central to seed conservation and crop management, must be recognized as key partners in climate adaptation initiatives.

Agricultural extension has a pivotal role in bridging scientific innovations with farmers' traditional knowledge. Rather than replacing indigenous practices, extension systems should facilitate the co-creation of locally relevant solutions that enhance productivity while preserving biodiversity and cultural heritage. Integrating modern technologies with community knowledge will enable tribal farming systems to become more resilient, sustainable, and economically viable.

The future of tribal hill oilseed farming lies not only in developing improved technologies but also in empowering farming communities to adapt, innovate, and lead the transformation towards climate-resilient agriculture. By investing in people, biodiversity, and knowledge systems, India can protect both the livelihoods of tribal farmers and the rich ecological heritage of its hill regions.

Key Messages

- Conserve indigenous oilseed landraces through community-managed seed banks to strengthen climate resilience.
- Promote climate-smart agronomic practices such as intercropping, organic nutrient management, moisture conservation, and rainwater harvesting.
- Strengthen participatory extension approaches that integrate farmers' traditional knowledge with scientific innovations.
- Empower women and community institutions as key stakeholders in seed conservation, technology dissemination, and climate adaptation.
- Improve market access, value addition, and policy support to enhance the profitability and sustainability of tribal oilseed farming.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine

Volume 04, Spcl. Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-30

BAMBOO-BASED LIVELIHOOD SYSTEMS: A SUSTAINABLE PATHWAY FOR RURAL DEVELOPMENT AND GREEN ECONOMY

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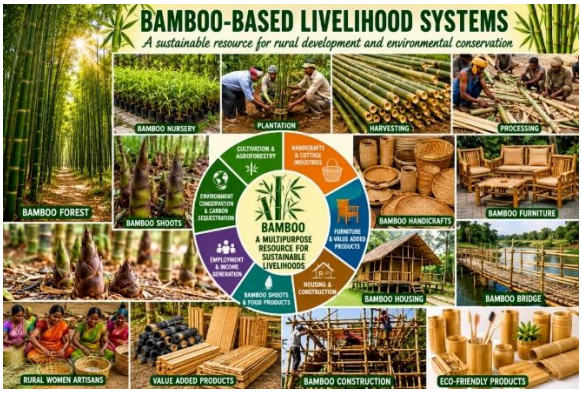
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Abstract

Bamboo is one of the fastest-growing and most versatile natural resources in the world. Often referred to as the "Green Gold" or "Poor Man's Timber," bamboo provides significant economic, ecological, and social benefits. In many developing countries, particularly India, bamboo-based livelihood systems support millions of rural households through employment generation, handicraft production, construction materials, furniture manufacturing, food products, and agroforestry enterprises. The bamboo sector contributes to poverty alleviation, environmental conservation, climate change mitigation, and sustainable rural development. Government initiatives such as the National Bamboo Mission have further enhanced opportunities for bamboo cultivation and value addition. Despite its immense potential, the sector faces challenges related to market access, processing infrastructure, technological adoption, and policy implementation. This article reviews the role of bamboo in livelihood generation, its ecological significance, value chain opportunities, challenges, and future prospects for sustainable development.

Keywords: Livelihood, Agroforestry, National Bamboo Mission, Sustainable Agriculture, Green Economy

Graphical Abstract



Introduction

Bamboo has long been recognized as one of nature's most versatile and valuable resources. Commonly referred to as "Green Gold," bamboo plays a significant role in supporting rural livelihoods, conserving natural resources, and promoting sustainable economic development. As one of the fastest-growing plants in the world, bamboo possesses unique biological and ecological characteristics that make it an ideal resource for addressing challenges related to poverty, unemployment, environmental degradation, and climate change. Throughout Asia, Africa, and Latin America, millions of people depend directly or indirectly on bamboo for income generation, food security, housing, handicrafts, and industrial products (Lobovikov et al., 2007; Yiping et al., 2010). India is among the world's richest countries in bamboo resources, with a wide range of bamboo species

distributed across diverse agro-climatic regions. The northeastern states, central India, and parts of southern India possess extensive bamboo forests that support traditional and modern livelihood activities (Tewari, 1992). For centuries, tribal and rural communities have utilized bamboo for constructing houses, making agricultural implements, weaving baskets, producing furniture, and manufacturing various household items. In recent years, increasing awareness regarding sustainable development and eco-friendly products has further enhanced the economic importance of bamboo-based enterprises (Banik, 2015).

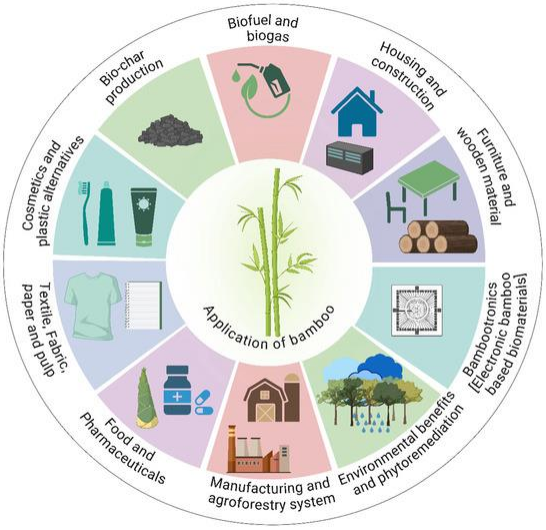


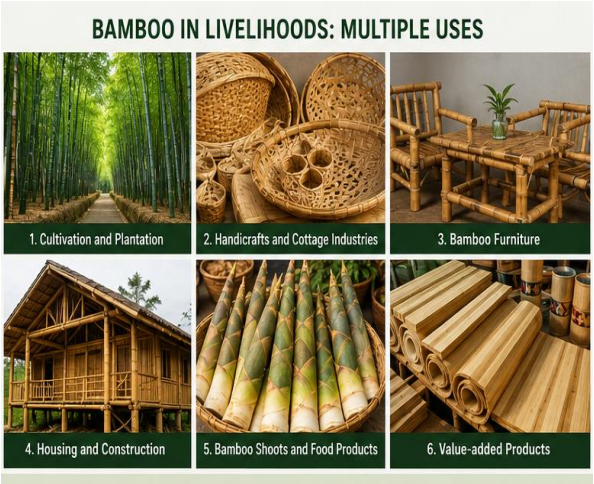
Fig. 1 Application of Bamboo

Bamboo as a Livelihood Resource

The significance of bamboo as a livelihood resource stems from its remarkable growth rate, adaptability, and multiple uses. Unlike conventional timber species that require several decades to mature, bamboo can be harvested within three to five years after planting. Once established, bamboo plantations continue to produce harvestable culms annually for several decades, ensuring a continuous source of income for farmers and entrepreneurs (Lobovikov et al., 2007).

Bamboo cultivation requires relatively low investment compared to many commercial crops and forestry species. It can grow successfully on degraded lands, marginal soils, and areas unsuitable for intensive agriculture. This characteristic makes bamboo particularly valuable for small and marginal farmers who often face limitations in land productivity and financial resources. By integrating bamboo into agroforestry systems, farmers can diversify their income sources while simultaneously improving soil health, conserving water, and reducing land degradation (Kumar et al., 2020).

The bamboo livelihood system encompasses a broad range of activities including nursery production, plantation establishment, harvesting, processing, value addition, transportation, marketing, and export. Each stage of the bamboo value chain generates employment opportunities and contributes to rural economic development. Consequently, bamboo-based enterprises have become an important instrument for poverty alleviation and livelihood enhancement in many developing countries (Yadav & Bisht, 2022).



Bamboo Cultivation and Farm-Based Livelihoods

Bamboo cultivation has emerged as an attractive option for farmers seeking sustainable and profitable alternatives to conventional agriculture. The increasing demand for bamboo products in domestic and international markets has encouraged many farmers to establish bamboo plantations on agricultural lands, field boundaries, and wastelands.

One of the major advantages of bamboo cultivation is its ability to generate regular income over a long period. After the initial establishment phase, mature culms can be harvested annually without replanting, thereby reducing cultivation costs and ensuring continuous returns. Bamboo also demonstrates remarkable resilience to drought, pests, and adverse environmental conditions, making it suitable for climate-resilient agriculture (Yiping *et al*., 2010).

Farmers practicing bamboo-based agroforestry systems often experience additional benefits such as improved soil fertility, enhanced biodiversity, reduced soil erosion, and increased carbon sequestration. The extensive root system of bamboo helps stabilize soil, prevent runoff, and improve water infiltration. These ecological services contribute to sustainable land management while supporting agricultural productivity (Nath *et al*., 2015).

The integration of bamboo with crops, fruit trees, and livestock enterprises further strengthens farm resilience and economic stability. Such diversified production systems provide multiple sources of income and reduce the risks associated with dependence on a single agricultural enterprise (Gupta et al., 2021.

Bamboo Handicrafts and Traditional Industries

Handicraft production represents one of the oldest and most widespread bamboo-based livelihood activities. Rural artisans have traditionally utilized bamboo to manufacture a variety of products including baskets, mats, fishing traps, storage containers, agricultural tools, household utensils, decorative items, and cultural artifacts. These products continue to play an important role in rural economies and cultural heritage preservation (Banik, 2015).

The handicraft sector provides employment opportunities for thousands of artisans, particularly women and tribal communities. Many households engage in bamboo craft production as a supplementary source of income during agricultural lean seasons. The skills associated with bamboo craftsmanship are often passed from one generation to another, contributing to the preservation of traditional knowledge and cultural identity (Kumar et al., 2020).

In recent years, changing consumer preferences and growing demand for eco-friendly products have created new market opportunities for bamboo handicrafts. Contemporary designs, improved product quality, and better marketing strategies have enabled artisans to access urban, national, and international markets. Government support programs and skill development initiatives have further strengthened the bamboo handicraft sector by enhancing technical capabilities and entrepreneurial skills among rural communities.

Bamboo Furniture and Value-Added Products

The bamboo furniture industry has emerged as one of the most promising sectors within the bamboo economy.

Bamboo possesses excellent strength-to-weight characteristics, durability, flexibility, and aesthetic appeal, making it suitable for manufacturing a wide range of furniture products. Chairs, tables, beds, cabinets, office furniture, garden furniture, and decorative items are increasingly being produced using bamboo as a sustainable alternative to conventional wood (Shanmughavel & Francis, 2016).

The growing global emphasis on environmentally friendly products has significantly increased the demand for bamboo furniture. Consumers are increasingly seeking renewable and sustainable materials that minimize environmental impacts. Bamboo furniture not only meets these expectations but also offers unique design possibilities and attractive visual appeal (Zhuang, 2018).

Beyond furniture production, bamboo is utilized in manufacturing numerous value-added products such as flooring materials, laminated boards, composite panels, textiles, charcoal, bioenergy products, paper, packaging materials, and handicraft accessories. These value-added industries generate substantial employment opportunities while increasing the economic value of raw bamboo resources.

The development of modern processing technologies has expanded the range of bamboo products available in domestic and international markets. Consequently, bamboo-based industries are becoming increasingly important contributors to rural industrialization and economic diversification (Singh et al., 2019).

Bamboo in Housing and Construction

Bamboo has been used as a construction material for centuries in many parts of the world. Its high tensile strength, flexibility, and durability make it an excellent material for building houses, bridges, scaffolding, roofing structures, flooring systems, and wall panels. In many rural areas, bamboo remains one of the most affordable and accessible construction materials available to local communities (Tewari, 1992).

The use of bamboo in modern construction has gained renewed attention due to increasing concerns regarding environmental sustainability and carbon emissions associated with conventional building materials. Bamboo-based construction systems require lower energy inputs and generate fewer greenhouse gas emissions compared to steel and concrete structures. Additionally, bamboo buildings often exhibit superior performance during earthquakes because of their flexibility and shock-absorbing properties (Shanmughavel & Francis, 2016).

The expansion of bamboo construction industries provides employment opportunities for farmers, artisans, builders, engineers, and entrepreneurs. It also contributes to affordable housing solutions while promoting sustainable resource utilization (Zhuang, 2018).

Bamboo Shoots and Food Security

Apart from its industrial and construction applications, bamboo also contributes to food security through the production of edible bamboo shoots. Young bamboo shoots are consumed as vegetables in many Asian countries and are particularly popular in northeastern India. These shoots are rich in dietary fiber, vitamins, minerals, proteins, and bioactive compounds that offer various health benefits (Nirmala et al., 2018).

The commercialization of bamboo shoots has created additional livelihood opportunities for rural communities. Farmers and entrepreneurs engage in the collection, processing, packaging, and marketing of fresh and processed bamboo shoot products.

Bamboo shoot pickles, fermented products, canned shoots, and ready-to-cook products are increasingly finding markets among health-conscious consumers.

The development of bamboo shoot processing industries not only generates income but also promotes nutritional security and value addition within rural economies (Nirmala et al., 2018).

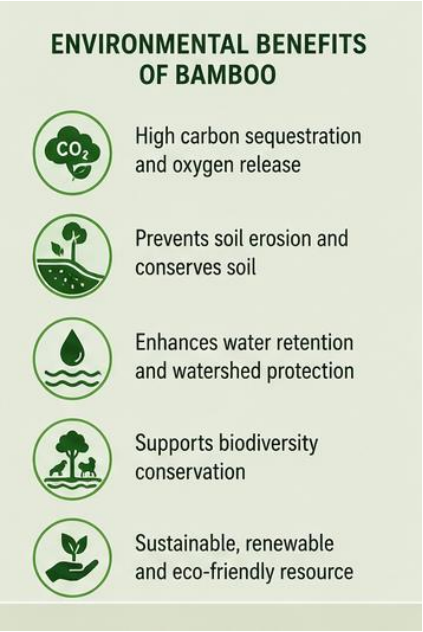
Environmental Benefits of Bamboo-Based Livelihood Systems

One of the most important advantages of bamboo-based livelihood systems lies in their environmental sustainability. Bamboo plantations provide a wide range of ecosystem services that contribute to environmental conservation and climate change mitigation (Yiping et al., 2010).

Bamboo is highly effective in capturing atmospheric carbon dioxide due to its rapid growth and high biomass production. Studies have demonstrated that bamboo plantations can sequester substantial quantities of carbon, thereby helping reduce greenhouse gas concentrations in the atmosphere. This characteristic makes bamboo an important component of climate-smart agriculture and sustainable land management strategies (Nath et al., 2015).

The extensive root network of bamboo plays a crucial role in soil conservation by reducing erosion, stabilizing slopes, and enhancing soil structure. Bamboo plantations are frequently utilized in watershed management programs and land restoration initiatives to rehabilitate degraded landscapes.

Furthermore, bamboo ecosystems provide habitat for various plant and animal species, thereby contributing to biodiversity conservation. The integration of bamboo into agricultural landscapes enhances ecological resilience while supporting sustainable livelihood development (Singh et al., 2019).



Government Initiatives and Policy Support

Recognizing the immense potential of bamboo, the Government of India has implemented several programs aimed at promoting bamboo cultivation, processing, and value addition. The National Bamboo Mission has emerged as a flagship initiative supporting the holistic development of the bamboo sector. The mission focuses on expanding bamboo cultivation, improving planting material quality, strengthening processing infrastructure, enhancing market linkages, and providing skill development opportunities.

Various state governments have also launched bamboo development programs to support farmers, artisans, and entrepreneurs. These initiatives have facilitated the establishment of nurseries, treatment facilities, processing units, and training centres. Financial assistance, technical guidance, and market

support have encouraged wider adoption of bamboo-based enterprises across rural areas.

Such policy interventions have significantly improved the prospects for bamboo-based livelihoods and contributed to the growth of a sustainable bamboo economy (Ministry of Agriculture and Farmers Welfare, 2018).

Challenges and Constraints

Despite its considerable potential, the bamboo sector faces several challenges that limit its contribution to rural development. One of the primary constraints is the limited availability of high-quality planting material and improved bamboo varieties. Many farmers lack access to technical knowledge regarding plantation establishment, management, and harvesting practices (Kumar et al., 2020).

Processing infrastructure remains inadequate in many bamboo-producing regions. Traditional processing methods often result in low product quality and reduced market competitiveness. Limited mechanization, insufficient treatment facilities, and inadequate value-addition technologies further restrict industrial development.

Market-related challenges include weak supply chains, inadequate market information, fluctuating prices, and limited access to export markets. Small-scale producers often struggle to connect with profitable markets due to logistical and institutional barriers (INBAR, 2021; Zhuang, 2018).

Addressing these challenges requires coordinated efforts involving government agencies, research institutions, private enterprises, and community organizations. Investments in research, technology development, skill enhancement, infrastructure creation, and market integration are essential for realizing the full potential of bamboo-based livelihood systems.

Future Prospects

The future of bamboo-based livelihood systems appears highly promising. Growing global demand for sustainable materials, eco-friendly products, renewable energy resources, and green construction materials is expected to drive substantial growth in the bamboo sector. Emerging industries such as engineered bamboo products, bamboo composites, bamboo textiles, biochar production, and carbon credit markets offer exciting new opportunities for rural entrepreneurs (INBAR, 2021; Zhuang, 2018).

Advances in processing technologies, digital marketing platforms, and value-chain development are likely to enhance the competitiveness of bamboo enterprises. Furthermore, increasing recognition of bamboo's role in climate change mitigation and sustainable development will continue to attract policy support and investment.

The integration of bamboo into agroforestry systems, watershed management programs, and rural development initiatives can create resilient livelihood opportunities while contributing to environmental sustainability and economic growth.

Conclusion

Bamboo-based livelihood systems represent an effective and sustainable approach to rural development, poverty reduction, and environmental conservation. The unique characteristics of bamboo, including rapid growth, multiple uses, ecological benefits, and economic viability, make it a valuable resource for promoting inclusive and sustainable

development. From cultivation and handicrafts to furniture manufacturing, construction, food processing, and industrial applications, bamboo generates diverse employment opportunities and strengthens rural economies (Yiping et al., 2010; INBAR, 2021).

With appropriate policy support, technological innovation, skill development, and market integration, bamboo has the potential to become a cornerstone of the green economy. Strengthening bamboo-based livelihood systems can significantly improve the well-being of rural communities while contributing to climate resilience, biodiversity conservation, and sustainable natural resource management.

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GreenariA
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An Agricultural Monthly e-Magazine

Volume 04, Spcl. Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-31

BEYOND HARVEST: INNOVATIONS SHAPING THE FUTURE OF OILSEED STORAGE AND PROCESSING

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Abstract

Oilseed crops such as soybean, sunflower, canola, groundnut, and sesame supply a major share of the world's edible vegetable oil and contribute significantly to food security and rural livelihoods. Despite improvements in crop production, substantial losses still occur after harvest because of inadequate drying, poor storage conditions, fungal contamination, and inefficient processing practices. Studies estimate that 6-22% of harvested oilseeds may be lost during post-harvest operations, resulting in economic losses and reduced food quality. Fortunately, advances in post-harvest science are helping address these challenges. Technologies such as improved drying systems, hermetic storage, smart monitoring sensors, green extraction methods, advanced packaging, and digital traceability are improving the preservation, safety, and value of oilseed products. These innovations not only reduce losses but also create opportunities for farmers and processors to access higher-value markets. This article explores how modern science is reshaping post-harvest management and helping ensure that more of what is harvested ultimately reaches consumers in a safe and nutritious form.

Introduction

Post-harvest losses in oilseeds remain a major concern worldwide. Estimates suggest that between 6% and 22% of harvested oilseeds are lost because of deterioration during drying, storage, transportation, and processing. Such losses reduce farmer income, increase pressure on natural resources, and contribute to food insecurity. Once seeds leave the field, they remain vulnerable to moisture, insects, fungi, and improper handling. These factors can reduce both the quantity and quality of harvested produce before it reaches processors or consumers.

Among the most serious threats is contamination by mycotoxins, toxic compounds produced by certain fungi under warm and humid storage conditions. Crops such as groundnut, soybean, sunflower, and rapeseed are particularly susceptible. Mycotoxin contamination not only lowers market value but also poses significant risks to human and animal health (Peng *et al.*, 2024; Abdolmaleki *et al.*, 2021).

Quality deterioration often begins long before visible damage appears. Oilseeds contain large amounts of unsaturated fatty acids that react with oxygen during storage. This process, known as oxidation, reduces nutritional quality, shortens shelf life, and causes undesirable flavours.

Soybean is especially vulnerable because of its high content of polyunsaturated fatty acids (Manjari *et al.*, 2026).

The challenge is further compounded by inadequate storage facilities, limited access to drying technologies, and insufficient post-harvest training in many oilseed-producing regions. While considerable attention has been devoted to increasing crop yields, reducing losses after harvest remains one of the most effective ways to improve food availability and farmer profitability.

Smarter Drying

Drying is one of the most important operations in post-harvest management. The moisture content of oilseeds largely determines whether they can be stored safely or become vulnerable to spoilage. Excess moisture encourages microbial activity, accelerates deterioration, and creates favourable conditions for fungal growth and mycotoxin production (Nath *et al*., 2024).

Traditional sun drying remains widely practiced because it is inexpensive and requires little infrastructure. Farmers typically spread seeds on tarpaulins, mats, or raised platforms and rely on sunlight to remove excess moisture. While effective under favourable weather conditions, this method often produces uneven drying and leaves seeds exposed to rainfall, dust, insects, and animals.

To overcome these limitations, improved solar and hybrid drying technologies are gaining attention. These systems combine solar energy with controlled airflow or supplementary heat sources, allowing more uniform and reliable drying. Better moisture management reduces the risk of fungal contamination and improves storage stability.

In larger production systems, aerated storage bins provide another effective approach. By moving air through stored seed, these systems gradually remove excess moisture while maintaining seed quality. Compared with conventional high-temperature drying methods, aeration can reduce energy consumption and minimize damage to sensitive oil components. Research has shown that drying methods influence not only storage performance but also the quality of the final oil. Properly dried seeds generally produce oils with better stability, flavour, and nutritional value (Sovilji et al., 2010). This highlights an important principle of post-harvest management: decisions made immediately after harvest often determine product quality months later.

Hermetic Storage

Once oilseeds have been dried to safe moisture levels, protecting them during storage becomes the next priority. Traditional storage systems often expose seeds to moisture fluctuations, insects, and fungal contamination, leading to substantial quality losses.

One of the most successful innovations in recent decades has been hermetic storage. The principle is simple: seeds are stored in airtight containers or bags that limit gas exchange with the external environment. As insects and microorganisms consume oxygen within the sealed space, oxygen levels decline and carbon dioxide concentrations increase. These conditions suppress insect activity and slow fungal growth without requiring chemical fumigants (Tubbs *et al.*, 2016).

For smallholder farmers, hermetic bags have proven particularly valuable because they are relatively inexpensive, easy to use, and highly effective. When seeds are properly dried before storage, hermetic systems can significantly reduce storage losses while preserving seed quality.

At larger scales, hermetic technologies include sealed silos, silo bags, and controlled-atmosphere storage systems. These approaches have enabled farmers and processors to store large quantities of oilseeds for extended periods while maintaining quality and reducing dependence on chemical treatments (Manjari *et al*., 2026). The success of hermetic storage depends on one critical condition: seeds must enter storage at safe moisture levels. If damp seeds are sealed inside airtight containers, deterioration can still occur. When combined with effective drying practices, however, hermetic storage provides one of the most reliable tools available for reducing post-harvest losses and preserving oilseed quality.

Green Extraction

For more than a century, hexane has been the dominant solvent used in industrial oil extraction because of its ability to recover a large proportion of oil from oilseeds. Despite its efficiency, concerns about solvent residues, environmental impact, and regulatory restrictions have encouraged the search for alternative extraction methods (Schoss & Kocevar Glavac, 2024).

One of the most widely adopted alternatives is cold pressing, particularly for oil-rich seeds such as rapeseed, sunflower, flaxseed, and pumpkin seed. Unlike solvent extraction, cold pressing relies solely on mechanical force to release oil from seeds. The process helps retain naturally occurring compounds such as tocopherols, phytosterols, carotenoids, and flavour compounds that may be affected by more intensive processing methods. Research has shown that processing conditions can influence both oil recovery and quality. Optimisation of factors such as press temperature and operating conditions can improve extraction efficiency while maintaining desirable oil characteristics (Todorovic *et al*., 2023).

Another important development is supercritical carbon dioxide (CO_2) extraction. Under specific temperature and pressure conditions, carbon dioxide behaves as a supercritical fluid and can efficiently extract oil without leaving solvent residues. After extraction, the CO_2 evaporates and can be recycled within the system (Schoss & Kocevar Glavac, 2024).

Comparative studies have shown that supercritical CO_2 extraction can produce oils with high levels of valuable bioactive compounds while avoiding thermal degradation of sensitive constituents. Recent comparisons among cold pressing, solvent extraction, subcritical butane extraction, and supercritical CO_2 extraction suggest that the suitability of a particular method depends on the desired oil characteristics, extraction efficiency, and processing objectives (Gu *et al*., 2025). These developments highlight a broader shift in oilseed processing towards technologies that combine oil quality, efficiency, and sustainability.

Smart Sensors and the Internet of Things

Advances in digital technology are changing how oilseeds are monitored during storage. Traditional methods often rely on periodic inspections, providing only limited information about conditions within storage structures. In contrast, sensor-based systems can continuously monitor critical parameters such as temperature, moisture, oxygen, and carbon dioxide concentrations.

Wireless sensor networks allow measurements to be collected from multiple locations within a storage facility and transmitted to remote monitoring platforms.

Such systems can identify developing problems before visible signs of deterioration appear, enabling timely management decisions (Safeer *et al*., 2024).

Recent studies integrating sensor networks, predictive models, and blockchain technologies have demonstrated the potential for accurate monitoring and forecasting of storage conditions. These systems can support decisions related to aeration, storage management, and quality preservation (Safeer *et al*., 2024).

Computer modelling is also increasingly being used to study airflow, heat distribution, and moisture movement within grain storage structures. According to Nath et al. (2024), simulation-based approaches provide an effective and relatively inexpensive way to optimise storage design and management practices before physical modifications are implemented. The integration of sensor networks, modelling tools, and digital monitoring systems is creating new opportunities for more precise and efficient post-harvest management.

Advanced Packaging for Quality Preservation

Packaging plays an important role in protecting oilseed products during storage, transportation, and marketing. Conventional packaging materials may allow oxygen transfer, which can contribute to oil oxidation and quality deterioration over time. To address these challenges, researchers are developing biodegradable, bio-composite, and nanotechnology-based packaging materials that provide improved protection while reducing environmental impacts. Degradable bioplastics and nanocellulose-based materials have attracted particular attention because of their ability to reduce oxygen transmission while offering environmentally friendly alternatives to conventional plastics (Rizzo, 2025).

Integrated post-harvest technologies that combine advanced packaging with other preservation approaches have been reported to reduce deterioration and microbial spoilage in several agricultural products (Rizzo, 2025). Nano-based coatings containing antimicrobial compounds such as silver nanoparticles, zinc oxide, and chitosan can further enhance product protection by limiting microbial activity and slowing quality degradation.

Another emerging development is intelligent packaging, which incorporates indicators that respond to changes in product condition. These systems can provide visual information related to freshness and quality, helping retailers and consumers assess product status without opening the package. Although some advanced packaging technologies remain costly, ongoing research and commercial development are expanding their potential applications in food systems.

Blockchain and Traceability: Transparency from Farm to Bottle

Demand for food products with verified quality, origin, and sustainability credentials continues to grow. In the oilseed sector, traceability systems are increasingly being explored as a means of documenting product movement and quality throughout the supply chain.

Blockchain technology provides a secure and tamper-resistant digital record of transactions and product history. A study by Vitaskos et al. (2024) developed a blockchain-based traceability system for olive oil supply chains that integrated Internet of Things (IoT) sensors and automated quality verification.

Similar approaches can be applied to oilseed crops such as canola, sunflower, and soybean.

A related study developed an agricultural traceability system combining blockchain and Radio Frequency Identification (RFID) technology to improve the efficiency of information management in agricultural supply chains (Li *et al*., 2024). Research has also shown increasing integration of blockchain, IoT, and machine learning technologies in agriculture for monitoring and quality assessment purposes (Safeer *et al*., 2024).

In oilseed supply chains, traceability systems can record information related to drying conditions, storage duration, moisture levels, and processing history. By linking these records throughout the supply chain, stakeholders can access information on product handling from production to final sale. As digital technologies continue to advance, blockchain-supported traceability systems are expected to play a greater role in improving transparency and quality assurance within agricultural value chains.

Valorising Oilseed By-products: Supporting a Circular Bioeconomy

Post-harvest innovation extends beyond preserving harvested seed and extracted oil. Increasing attention is being given to the utilisation of by-products generated during oil extraction.

After oil is removed from oilseeds, a protein-rich press cake or meal remains. Traditionally, these materials have been used primarily as animal feed. However, research has shown that oilseed cakes contain a range of compounds including proteins, dietary fibre, polyphenols, tocopherols, phytates, and other bioactive constituents with potential value in food, nutraceutical, and pharmaceutical applications.

Studies on oilseed processing have demonstrated that defatted cakes can retain substantial quantities of protein and dietary fibre after extraction (Sovilji et al., 2010). This has increased interest in recovering additional value from materials that were previously considered low-value by-products.

The circular bioeconomy concept promotes the efficient use of biomass through multiple stages of utilisation. Under this approach, oil is extracted first, valuable compounds are subsequently recovered from the remaining cake, and residual biomass may be used for energy production or soil amendment. Such approaches improve resource utilisation and reduce waste generation. Integrated post-harvest systems that support food safety, nutrient preservation, waste reduction, and resource recovery are increasingly aligned with broader sustainability goals (Rizzo, 2025; Nath et al., 2024).

Conclusion and Future Prospects

Post-harvest management remains a critical component of oilseed production, as substantial losses continue to occur due to inadequate drying, poor storage conditions, fungal contamination, and processing inefficiencies. Advances in drying technologies, hermetic storage, green extraction methods, smart monitoring systems, advanced packaging, and digital traceability are improving the preservation, safety, and value of oilseed products while reducing avoidable losses.

The wider adoption of these technologies will depend not only on their availability but also on access to appropriate infrastructure and technical knowledge. Evidence indicates that

technology-based interventions are most effective when combined with training and capacity-building programmes, particularly for storage management and mycotoxin control (Stathers et al., 2024). Future efforts should therefore focus on promoting affordable, scalable, and farmer-oriented solutions that can be adopted across diverse production systems. Continued investment in post-harvest innovation, infrastructure, and knowledge dissemination will be essential for improving resource-use efficiency, maintaining product quality, and strengthening the sustainability of oilseed value chains.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine

Volume 04, Spcl. Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-32

SOCIO-ECONOMIC, GENDER AND POLICY DIMENSIONS OF OILSEED ADOPTION AND LIVELIHOOD SECURITY

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Abstract

Oilseeds play important role in India's agricultural economy by contributing to food security, rural livelihoods, nutritional well-being, and industrial development. As the second most important group of field crops after cereals, oilseeds support income generation, crop diversification, and sustainable farming systems, particularly in rain-fed regions. Women contribute significantly across oilseed value chains, although gender-based constraints continue to limit their access to resources and decision-making. To enhance productivity and reduce import dependence, the Government of India has implemented several initiatives, including NMOOP, CFLDs, and the National Mission on Edible Oils. These interventions aim to strengthen domestic production, improve farmer livelihoods, and achieve edible oil self-reliance.

Key words: Oilseed, Livelihood, NMOOP, CFLD

Introduction

Agriculture is the backbone of India's economy, employing nearly half of the workforce and serving as a cornerstone for food security and rural livelihoods (FAO, 2021). Oilseeds not only supply edible oils essential for domestic consumption but also provide raw materials for industries producing biofuels, livestock feed, and other processed goods. The nine primary oilseed crops groundnut, rapeseed-mustard, soybean, sunflower, sesame, safflower, niger, castor, and linseed occupy 14.3% of the gross cropped area, contribute 12–13% of dietary energy, and account for about 8% of agricultural exports (GoI, 2025). India ranks fourth after the USA, China, and Brazil in oilseed production, accounting for about 20% of the global oilseed area and 10% of oil production. Major oilseed-producing states include Rajasthan, Madhya Pradesh, Gujarat, Maharashtra, Haryana, Uttar Pradesh, West Bengal, Karnataka, Tamil Nadu, and Telangana. Among them, Rajasthan (24%), Madhya Pradesh (22%), Gujarat (18%), and Maharashtra (14%) contribute the largest share of total oilseed production.

Oilseeds support crop diversification and farm incomes, particularly in rain-fed and resource-poor regions. Strengthening domestic oilseed production aligns with Sustainable Development Goal 2 (Zero Hunger) by promoting resilient agricultural practices, reducing rural poverty, and improving access to safe and affordable food.

As a major source of dietary fats, energy, and fat-soluble vitamins, oilseeds help combat hidden hunger and improve calorie intake, particularly among underprivileged and malnourished populations.

Socio-Economic Dimensions

Oilseed cultivation plays a significant role in rural economies, particularly in developing countries where agriculture is a primary source of livelihood. In India, oilseeds constitute the second most important group of field crops after cereals. These crops provide income opportunities for millions of farmers and enable smallholders to participate in domestic and global markets. In addition to oil production, oilseeds contribute to sustainable farming through crop rotation, which improves soil health and overall farm productivity. Their processing into edible oil, value addition generates employment, and reduces post-harvest losses. Despite, above cited potential farmers are facing Challenges viz., non-availability of quality seeds or improved varieties, fertilizer, insecticides and pesticides, sufficient storage and processing infrastructure. Socio-economic dimension such as family size, gender, age, education, land tenure, and occupation significantly impacts on practicing oilseed cultivation. Large farmers tend to have higher incomes and better access to advanced agricultural inputs, credit facilities, and market linkages, enabling them to adopt improved technologies. In contrast, marginal and small farmers often struggle with limited resources, inadequate institutional support, and lower bargaining power, which hinders their productivity and profitability despite owning sizeable landholdings in some cases.

Gender Dimensions

Farm women are being considered as invisible work force in agriculture even though they participate in most of the agricultural operations. Women contribute meaningfully across the entire oilseed and edible oil ecosystem-from cultivation and research to processing, trade, and enterprise. Their work strengthens value chains, supports rural livelihoods, and contributes to more resilient food systems. Despite their significant contributions, women face several challenges that hinder their productivity and economic empowerment. Limited access to land, credit, agricultural inputs, and education remains a persistent barrier for women farmers, leading to reduced productivity and income disparities when compared to their male counterparts. Furthermore, studies highlight how cultural norms and gender biases limit women's access to leadership roles in decision-making processes. Despite these challenges, women in agriculture have shown remarkable resilience and adaptability. Empowering women through policy reforms, training programs, and improved access to resources has been linked to increased agricultural productivity, enhanced food security, and better community well-being.

Policy Dimensions

The Government of India has introduced several programmes to increase oilseed production, improve productivity, and livelihood security of farmers. Early initiatives were such as Integrated Scheme on Oilseeds, Pulses, Oil Palm and Maize (ISOPOM, 2004), aimed at enhancing production and resource-use efficiency, National Mission on Oilseeds and Oil Palm (NMOOP, 2014) was launched to increase the area, production, and productivity of oilseeds and oil palm. Further, In the year 2015-16, the programme 'Cluster Front Line Demonstrations' (CFLDs) on Oilseeds was initiated by the Ministry of Agriculture and Farmer's welfare, Government of India, New Delhi under National Mission on Oilseeds and Oil Palm (NMOOP). The division of Agricultural Extension, Indian Council Agricultural Research (ICAR), New Delhi put responsibility to lay out CFLDs on important oilseed crops such as sesamum, rapeseed and linseed through Krishi Vigyan Kendras (KVK) through eleven ICAR-Agricultural

Technology Application Research Institutes (ATARI) all over India.

Nonetheless, in the year 2021 government of India launched National Mission on Edible Oils (NMEO) aims to strengthen the country's oilseed ecosystem and achieve Atmanirbhar Bharat in edible oil production. The NMEO–OP (Oil Palm) aims to bring 6.5 lakh hectares under oil palm cultivation by 2025–26 and increase crude palm oil production to 28 lakh tonnes by 2029–30. By November 2025, 2.50 lakh hectares have been covered, bringing the total coverage of oil palm in the country to 6.20 lakh hectares. Crude Palm Oil (CPO) production has risen from 1.91 lakh tonnes in 2014-15 to 3.80 lakh tonnes in 2024-25. NMEO–OS (Oil Seeds) aims to increase oilseed production from 39 to 69.7 million tonnes by 2030–31 through cluster-based interventions and improved seed systems.

Conclusion

Oilseeds are a key component of India's agricultural economy, contributing to food security, nutrition, rural livelihoods, and industrial development. They promote crop diversification and income generation, particularly in rain-fed areas. However, their potential is constrained by limited access to quality inputs, credit, technology, and infrastructure, especially for small and marginal farmers. Women play a significant role in oilseed cultivation and value chains, yet their contributions often remain undervalued due to unequal access to land, credit, education, and decision-making opportunities. Strengthening gender-inclusive policies is essential for improving productivity and empowerment. Government initiatives such as NMOOP, CFLDs, and the National Mission on Edible Oils (NMEO) have supported production growth through technology dissemination, cluster-based development, and expansion of oilseed cultivation. Achieving edible oil self-reliance and enhancing farmer livelihoods will require continued policy support, socio-economic inclusiveness, and greater recognition of women's roles in the sector.

GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine

Volume 04, Spcl. Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-33

EMPOWERING TRIBAL WOMEN SHGS THROUGH MECHANIZED OIL EXTRACTION ENTERPRISES

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Abstract

Traditional post-harvest agricultural processing in India's tribal corridors sits at a difficult intersection of manual labour, low technical yields, and economic marginalisation. Tribal women, who form the backbone of minor oilseed cultivation, have long endured primitive extraction methods that demand intense physical effort while returning minimal financial reward. This paper evaluates a deliberate structural intervention: deploying low-cost, gender-friendly, small-scale mechanised oil expellers directly to women-led Self-Help Groups (SHGs), bypassing capital-intensive centralised mills. Through a market-led value chain framework, we examine how transferring technological ownership to the grassroots reduces physical drudgery, realigns household resource allocation, improves rural nutrition, and rebalances local market dynamics in favour of marginalised tribal communities.

Key Words: Tribal women empowerment, Small-scale oil expellers, Self-Help Groups (SHGs), Decentralised agro-processing

Introduction

In India's central and eastern tribal belts, minor oilseeds niger (Guizotia abyssinica), sesame (Sesamum indicum), linseed (Linum usitatissimum), and groundnut (Arachis hypogaea) are integral to rain-fed farming systems. These crops are resilient, adapted to poor soils, and represent a vital source of emergency cash income for smallholder farmers. Yet a stark developmental paradox persists: the tribal micro-regions that produce a significant share of the nation's minor oilseeds remain among the most economically marginalised.

The problem lies not in crop productivity but in what happens after the harvest. For generations, processing raw seeds into edible oil has been an exhausting manual task shouldered almost entirely by tribal women. Using stone mortars and wooden presses, women spend hours of intense physical labour to extract small quantities of oil. This method is so inefficient that between 10 and 15 per cent of extractable oil remains trapped in the residual cake. Because individual households lack the means to process their harvests efficiently, they are pushed into distress sales at the farm gate well below the Minimum Support Price. The same families later repurchase processed cooking oil from urban centres at substantially higher prices.

This paper examines an alternative: introducing small-scale, low-horsepower oil expellers owned and managed by women-led SHGs, converting tribal women from raw-material suppliers into micro-enterprise owners who govern their own local value chain.

2. Why Tribal Farmers Keep Growing, Yet Never Stop Struggling!

Despite being custodians of diverse oilseed crops and possessing generations of indigenous knowledge, tribal farming communities continue to remain economically vulnerable. The paradox lies in the fact that regions that contribute significantly to the cultivation of minor oilseeds such as niger, sesame, linseed, and groundnut are themselves deprived of the benefits arising from value addition and market participation. Limited access to efficient processing technologies, inadequate storage infrastructure, fragmented production, and immediate cash requirements often compel farmers to sell their harvest soon after production at prices far below their actual market value. This distress-driven marketing pattern transfers a substantial portion of the economic gains to traders and distant processing industries.

The burden of this inefficient system falls disproportionately on tribal women, who are deeply involved in sowing, harvesting, drying, storage, and traditional oil extraction activities. Conventional methods using stone mortars and wooden presses demand hours of strenuous labour and yet fail to recover the full oil content of the seed. As a result, a significant quantity of valuable oil remains trapped in the residual cake, leading to both nutritional and economic losses. Ironically, households that produce oilseeds are often compelled to purchase refined cooking oil from urban markets at much higher prices, creating a situation in which producers become dependent consumers of their own produce.

This cycle represents not merely a technological gap but a broader issue of unequal distribution of value within the agricultural supply chain. The absence of local processing facilities and collective market institutions prevents tribal communities from retaining wealth generated from their own resources. Consequently, agricultural production alone has been unable to translate into improved livelihoods, nutritional security, or financial resilience. Understanding this sequence of production, distress sale, external value addition, and expensive repurchase is essential for identifying interventions that can restore economic control to the producers themselves. The interconnected stages that constitute this persistent paradox are illustrated in Flowchart 1.

Flowchart 1: The Tribal Oilseed Paradox

Tribal Women Cultivate Minor Oilseeds *Niger, sesame, linseed, groundnut on rain-fed land*
▼
Manual Extraction: Stone Mortar / Wooden Press *Days of labour • 10–15% oil lost in residue cake*
▼
Forced Distress Sale Below MSP *Traders exploit poor storage and immediate cash need*
▼
Household Re-Purchases Oil at Inflated Price *Often adulterated, sourced from distant urban mills*
▼
Net Outcome: Economic Marginalization Deepens

Market-Led Value Chains and Institutional Frameworks

Transitioning tribal oilseed farming to a sustainable market-oriented enterprise requires restructuring how commodities move from field to consumer. A market-led value chain relies on institutional aggregation that allows smallholders to function with the leverage of a collective enterprise.

Decentralised Bulk Aggregation

By organising into village-level SHGs and federating into Farmer Producer Organisations (FPOs), tribal women can aggregate raw oilseeds within their own communities. This directly addresses the core bottleneck of fragmented volumes and high transport costs. When an SHG cluster aggregates multiple metric tonnes at a single village point, it establishes a reliable supply baseline for the local expeller, stabilises production schedules, and strengthens collective bargaining power.

Localised Processing and Waste Valorisation

Localised mechanical expellers transform the processing economics. Seeds are cleaned, graded, and processed within the village, which means the financial markup that ordinarily flows to urban mills stays entirely within the local economy. Additionally, residual oil cake traditionally discarded or sold cheaply can be packaged and sold as high-protein animal feed. This secondary income stream often covers the daily operational costs of running the machinery.

Branding and Market Integration

With consistent extraction quality, SHG collectives can evolve from selling unbranded bulk oil to marketing specialised products. Tribal minor oilseeds particularly niger and organic sesame are increasingly valued in urban centres for their purity and nutritional profile. Simple traceability tools like QR-coded packaging, pesticide-free certification, and Geographical Indication (GI) tags help these collectives access premium retail shelves, organic food chains, and e-commerce platforms.

Flowchart 2: SHG-Managed Oilseed Value Chain

Seed Cultivation on Tribal Farmland
▼
Village-Level Aggregation via SHG / FPO
▼
Localised Mechanical Expelling (2–5 HP, single-phase)
▼
Filtered Edible Oil + High-Protein Oil Cake
▼
Branding, QR Traceability, GI Certification
▼
Local Haats • Urban Organic Retail • Institutional Procurement

Socio-Economic and Gender Dimensions

Reducing Physical Drudgery and Time Poverty

Modern small-scale expellers with push-button controls, ergonomic hoppers, and automated filtration eliminate the gruelling labour of traditional extraction. A process that once consumed full days is completed in one to two hours. This directly addresses what development researchers call 'time poverty': the chronic deficit of free time experienced by

women who carry both productive and domestic responsibilities. Hours freed from manual oil extraction can be reinvested in adult literacy, community leadership, children's education support, or diversified activities such as mushroom cultivation and apiculture.

Financial Autonomy and Household Impact

When technology ownership shifts to women's SHGs, revenue from oil processing and oil-cake sales flows directly into bank accounts managed by the women themselves. This shift in financial control has a well-documented multiplier effect at the household level. On nutritional security, SHG members retain cold-pressed edible oil for home use, directly improving fat and micronutrient intake for children and nursing mothers. On education and healthcare, research consistently shows that when women control household finances, a larger share goes toward children's school fees and medical care (Kochar et al., 2022). Finally, financial surpluses strengthen the SHG's internal lending pool, reducing members' dependence on predatory moneylenders.

Extension Strategies and Institutional Support

Three-Tier Institutional Model

Effective support connects policy makers, regional experts, and local operators across three levels:

Level	Responsibilities
Macro — State / National (Agricultural Depts, ICAR, FPO Federations)	Secure public funding, set regional targets, manage market contracts and GI registration
Meso — District / KVK (Krishi Vigyan Kendras, Agribusiness Hubs)	Mechanical training, oil safety testing, regional packaging support
Micro — Village SHG (Women Operators, CRPs)	Daily expeller operation, seed collection, processing services for neighbouring farmers

Community Resource Persons

Selected SHG members are trained as Community Resource Persons (CRPs), receiving hands-on instruction in machine operation, routine maintenance, and electrical safety. Keeping this knowledge within the village prevents long operational shutdowns during minor failures. All training materials are delivered in local languages through visual guides and practical demonstrations.

Case Studies

DAY-NRLM Odisha and Madhya Pradesh

Under the Deendayal Antyodaya Yojana National Rural Livelihoods Mission (DAY-NRLM), village organisations in Mandla (MP) and Rayagada (Odisha) were equipped with single-phase 3–5 HP oil expellers with filter presses. Members could pay a small per-kilogram processing fee or sell seed directly to the SHG at a fair price. Net profit margins per quintal increased by 32–45% through direct sale of filtered oil at regional markets. Oil cake was quickly absorbed by local dairy farmers, and units achieved financial self-sufficiency within their first operating year (DAY-NRLM Portal, 2024).

ICAR-IIOR Participatory Technology Transfer

The ICAR–Indian Institute of Oilseeds Research, in partnership with regional KVKs, deployed gender-friendly expellers as live demonstration sites. Women could observe firsthand how higher oil-content certified seed varieties produced greater output per machine hour. This visible link encouraged widespread adoption of improved varieties and triggered the formation of village seed-saving networks for high-yield sesame and groundnut strains (ICAR-IIOR, 2024).

Kudumbashree Kerala

Kerala's Kudumbashree Mission structured women's micro-enterprises around a Group Liability framework: teams of 4–10 women accessed subsidised bank loans to set up localised processing units. The programme succeeded through strict quality standards, clean packaging, and guaranteed institutional demand state bodies sourced oil from these units for school mid-day meals and childcare centres. This guaranteed market gave units the financial stability to scale sustainably, offering a transferable template for tribal contexts elsewhere.

Constraints and Practical Challenges

Challenge	**Mitigation**
Electrical Connectivity Voltage fluctuations and outages are common in remote tribal hamlets.	Use 2–3 HP energy-efficient motors that handle voltage variation; invest in solar-powered hybrid expeller units for off-grid areas.
Seasonal Supply Variation Oilseed harvesting is seasonal, risking machinery idleness in the off-season.	Train SHGs to diversify across crops (niger, mustard, sesame, mahua) by season, ensuring the facility runs year-round.
Technical Maintenance Major mechanical breakdowns require specialised support unavailable in remote areas.	Mandate two-year service agreements with suppliers; build district-level technician capacity for rapid response.

Policy Recommendations

Scaling localised, gender-friendly mechanisation into a coordinated national programme requires four complementary policy actions. First, a dedicated NMEO funding window should provide up to 80% subsidy on small-scale processing equipment for registered women-led SHGs and tribal FPOs. Second, RKVY and MGNREGA funds should be converged to finance processing sheds, grain-drying floors, and secure village-level storage facilities. Third, state governments should mandate that a portion of edible oil procured for school mid-day meals and Integrated Child Development Services be sourced from women-managed SHG units, ensuring guaranteed institutional markets. Finally, agricultural engineering institutes should

develop and certify women-centric machinery standards that prioritise reduced weight, enhanced safety, and energy efficiency, embedding ergonomic design at the heart of technology adoption.

Four-Pillar Policy Framework

Pillar 1 - Targeted Subsidies (NMEO-OP)

Pillar 2 - Rural Infrastructure (RKVY + MGNREGA)

Pillar 3 - Guaranteed Institutional Markets

Pillar 4 - Ergonomic Technology Standards

Conclusion

Empowering tribal women through small-scale, gender-friendly mechanised oil expellers addresses far more than a processing inefficiency. It removes hours of daily physical burden, shifts financial control back to the producers, and shows that targeted local technology can bring lasting socio-economic change to communities that mainstream development has long bypassed.

By shifting from centralised industrial refining to community-managed value addition, this model helps tribal communities retain agricultural wealth, secure stronger market positions, and build more resilient livelihoods. As India works toward greater self-reliance in edible oil production, the most durable path to sustainability begins with supporting the women who plant the seeds — and building the structures that ensure they also reap the returns.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine

Volume 04, Spcl. Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-34

FROM FIELD TO MARKET: ROLE OF AGRICULTURAL EXTENSION IN SCALING-UP OILSEEDS TECHNOLOGIES

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Abstract

Agricultural extension is the invisible engine of agricultural transformation. In the context of oilseed development, it is the critical bridge between research innovation and farmer practice, between government policy and ground-level implementation, and between smallholder vulnerability and rural market opportunity. As India works to close its massive edible oil import gap, reduce rural poverty, and improve nutritional security for its 1.4 billion citizens, a revitalised extension system, market-oriented, digitally empowered, gender-inclusive, and institutionally well-connected is not a luxury but an operational necessity. The journey from a field to a cold-pressed oil bottle on a supermarket shelf in Delhi is long, complex, and fraught with points of value loss and farmer exploitation. Shortening and improving this journey through stronger FPO linkages, digital market platforms, participatory research, and climate-smart advisory services requires the concerted energy of researchers, extension professionals, policymakers, market actors, and farmers themselves working in genuine partnership. Agricultural extension education, as a discipline, has a special responsibility in this endeavour. This article explores how market-led value chains, Socio-economic integration, and robust extension services can together pave the way for a new era of sustainable oilseed development.

Introduction

Oilseeds are the unsung heroes of Indian agriculture. Grown across nearly 29–30 million hectares from the golden mustard fields of Rajasthan to the groundnut plains of Gujarat and the sunflower belts of Karnataka, they collectively account for roughly 8–10 per cent of the country's gross cropped area (ICAR, 2022). Beyond the farm gate, oilseeds fuel a massive edible oil economy, provide protein-rich oilcake for livestock, and supply raw materials to the oleochemical and soap industries. More fundamentally, they anchor the dietary fat intake of hundreds of millions of Indians, especially the rural poor who depend on locally crushed, affordable oils for everyday cooking.

Yet, India's oilseed story is one of unfulfilled potential. Despite being the world's fourth-largest edible oil producer, the country imports edible oils worth more than ₹1.5 lakh crore every year, a glaring indicator of the persistent gap between domestic production and consumption (USDA, 2023). This gap is not primarily a technology problem; improved varieties, precision cultivation practices, and post-harvest innovations already exist on research-station shelves. The real bottleneck lies upstream and downstream; fragmented value chains, poor market linkages, limited access to credit and inputs for smallholder farmers, and perhaps most critically, a weak and under-resourced agricultural

extension system that struggles to translate research breakthroughs into farm-level adoption.

Recognising this, the Government of India launched the National Mission on Edible Oils-Oilseeds (NMEO-Oilseeds) in 2024 with an outlay of ₹10,103 crore, aiming to reduce import dependence and to raise domestic oilseed production (Government of India, 2024). However, policy ambition alone cannot transform fields. What is needed is a reinvigorated, farmer-centric, market-integrated agricultural extension system that catalyzes policy intent and ground reality.

Oilseed Value Chain Development and Agribusiness Opportunities

Understanding the oilseed value chain is the first step toward strengthening it. The chain begins at the input end with quality seeds, fertilisers, irrigation, and crop protection and moves through production, primary processing (cleaning, threshing, drying), secondary processing (oil extraction, refining, packaging), storage, transportation, and finally, retail and consumption. At each node, value can be added, and can also be lost through inefficiency, spoilage, or exploitation (Birthal *et al.*, 2020). For millions of smallholder oilseed farmers, the tragedy is that they participate only at the lowest-value end of this chain, selling raw produce to local intermediaries while processors, traders, and retailers capture the lion's share of the consumer rupee.

Farmer-Producer Organisations and Cooperative Models

This extractive dynamic is slowly changing as a result of a growing network of Farmer-Producer Organisations (FPOs) and oilseed cooperatives. Under the Central Government's scheme to promote 10,000 FPOs, oilseed collectives in Maharashtra, Madhya Pradesh, and Rajasthan have begun to pool produce, negotiate collectively, and access larger markets with better price realisation.

A compelling example from the Vasundhara Oilseeds FPO in Rajasthan, which aggregated mustard output from over 3,000 smallholder households, established a community-run mini oil mill, and supplied branded cold-pressed mustard oil directly to urban retailers effectively, bypassing three layers of middlemen and improving farmer net returns by 20–25 per cent (Singh & Vatta, 2019). The Gujarat Cooperative Milk Marketing Federation (GCMMF) offers a parallel institutional model, i.e. collective ownership, democratic governance, and shared profits that the oilseed sector has much to learn from.

Market Access and Value Addition in Tribal and Resource-Poor Regions

For tribal communities and resource-poor farmers in central and eastern India, non-conventional oilseeds such as mahua, sal seed, neem, and karanja hold significant livelihood potential. Tribal belts of Chhattisgarh, Odisha, and Jharkhand harbour centuries of traditional knowledge about collecting and processing these forest-based oilseeds. Women's Self-Help Groups (SHGs) supported by organisations like CYSD (Centre for Youth and Social Development) in Odisha have begun converting mahua seeds into artisanal cooking oil and skincare products, linking tribal producers directly to urban niche markets through extension-facilitated supply chains (Saxena, 2012).

These initiatives illustrate that value addition need not require large capital investment but requires extension support, market intelligence, and institutional connectivity.

TRIFED (Tribal Cooperative Marketing Development Federation of India) has created platforms for marketing tribal oilseed produce, while the PMFBY crop insurance scheme and MSP operations for oilseeds provide a financial safety net for risk-averse tribal cultivators. The extension challenge is to connect farmers to these schemes and to the processing and marketing infrastructure that transforms raw oilseeds into high-value products.

Socio-Economic Integration and Livelihood Security

Oilseed farming is far more than a cropping system; it is an integrated livelihood system for millions of households. When oilseed technologies are successfully adopted, the income effects are substantial. Studies document that adoption of improved groundnut varieties can boost yields by 40–60 per cent over traditional varieties under comparable management conditions, translating directly into higher household net incomes and improved consumption expenditure (Birthal *et al.,* 2012).

Beyond the primary crop, oilseed byproducts such as expeller cake as animal feed, husks as fuel, and extracted oil as a processing input create diversified income streams that buffer farm households against seasonal price volatility.

Gender Dimensions: Women as Oilseed Champions

Women are, in practice, the backbone of oilseed production systems, yet they remain strikingly invisible in policy frameworks and extension delivery. From sowing, weeding, and harvesting to post-harvest processing and local sale, women perform the majority of oilseed-related labour in most farming households. In tribal and semi-arid regions, women are often the de facto managers of homestead oilseed plots and the primary processors of oil for household consumption and barter (Pattnaik et al., 2018).

Empowering women through gender-responsive extension, dedicated training camps, women extension agents, access to small-scale processing equipment, and linkage to women's enterprise support schemes is not merely a matter of equity but an efficiency imperative. The Mahila Kisan Sashaktikaran Pariyojana (MKSP), implemented through NABARD and partner NGOs across Jharkhand, Odisha, and Madhya Pradesh, has demonstrated how gender-sensitive oilseed training and collective marketing can dramatically improve women's economic agency and household nutritional outcomes.

Tribal Inclusion and Smallholder Farmers

India's tribal communities are custodians of agro-biodiversity and traditional oilseed knowledge, yet they remain among the most marginalised participants in formal agricultural value chains. Under the Forest Rights Act (2006), tribal households hold cultivation rights over forest land, much of which is ecologically suitable for oilseed crops.

Extension programs targeting these communities must be culturally appropriate, delivered in local languages, and routed through trusted community institutions rather than distant government offices. The convergence of tribal livelihood schemes, Van Dhan Kendras, TRIFED market linkages, and MKSP livelihood platforms with mainstream oilseed extension can create a powerful institutional synergy that no single program can achieve alone.

Policy instruments such as PM-KISAN income transfers, subsidised seed kits under the National Food Security Mission and targeted credit through Kisan Credit Cards provide a vital

enabling environment. The extension system's role is to ensure that these entitlements actually reach the most marginalised farm households, rather than being captured by the relatively better-off (Government of India, 2023).

Agricultural Extension for Scaling-Up Oilseed Technologies

Agricultural extension plays a significant role in bridging the vast gap between laboratory-proven oilseed technologies and farmer fields. Extension, being the systematic process of communicating knowledge, facilitating learning, and linking farmers to markets and services is the connective tissue of agricultural development. India's oilseed sector needs not just more extension, but better, more responsive, more market-oriented extension that reaches every farmer, regardless of their gender, caste, land holding, or geography.

Participatory Approaches: Learning by Doing

Farmer Field Schools (FFS) for oilseeds, pioneered by FAO, have been widely adopted across Andhra Pradesh, Telangana, and Karnataka, creating season-long learning communities where groundnut, sunflower, or sesame farmers experiment in their own fields, observe, analyse, and make informed management decisions (FAO, 2021). The results are striking, viz., FFS graduates not only adopt improved practices at higher rates, but also serve as informal knowledge hubs for neighbouring farmers, catalysing second-order diffusion within their communities.

Frontline Demonstrations (FLDs) conducted by Krishi Vigyan Kendras (KVKs) and ICAR institutes remain the foundation of technology dissemination in Indian oilseed farming. By hosting demonstration plots of newly released varieties such as GJG-31 groundnut, RH-749 mustard, or MAUS-162 soybean on farmers' own fields, FLDs provide a credible, locally visible proof of concept that extension talks and pamphlets simply cannot replicate.

When combined with Farmer-to-Farmer Extension (F2FE), where trained lead farmers share knowledge with their neighbours in the same dialect and through trusted social networks, FLDs create a powerful ripple effect. In the Kalahandi district of Odisha, lead tribal farmers trained by CYSD catalysed the adoption of improved sesame varieties among hundreds of households through peer demonstrations and community seed distribution (CYSD, 2022).

ICT-Enabled Advisory Services and Digital Extension

India's smartphone revolution has opened transformative possibilities for agricultural extension. Digital platforms such as the Kisan Suvidha app, m-Kisan SMS advisory, and the IFFCO Kisan mobile service now deliver real-time crop advisories, weather forecasts, pest alerts, and market price information directly to farmers' handsets (Mittal & Mehar, 2012).

The e-NAM (National Agriculture Market) platform has improved price discovery for oilseed farmers in APMC-connected mandis, reducing information asymmetry between buyers and sellers. YouTube channels run by progressive oilseed farmers and extension agents providing content in local language on sowing techniques, pest management, and post-harvest handling have garnered millions of views, demonstrating an enormous and largely untapped appetite for practical digital agricultural content.

The Digital Agriculture Mission (2021–2025) aims to create an Agri Stack, a unified digital architecture linking soil health data, weather, credit, insurance, and market

information at the plot level that could enable precision extension advisory for oilseed farmers (Ministry of Agriculture & Farmers Welfare, 2022). When integrated with extension delivery systems, this infrastructure could shift advisories from generic broadcasts to personalised recommendations based on a farmer's specific soil type, crop variety, and micro-climatic conditions, resulting in a quantum leap in extension effectiveness.

Capacity Building, Skill Development, and Entrepreneurship

Scaling up oilseed technologies requires not only informed farmers but also a new generation of rural agripreneurs and professionally skilled extension workers. KVK entrepreneurship development programmes, ATMA (Agricultural Technology Management Agency) vocational training camps, and skill modules integrated with the Pradhan Mantri Kaushal Vikas Yojana have helped rural youth establish oilseed processing enterprises, portable expeller units, mini refineries, and value-added packaging micro-enterprises (NRLM, 2022).

Women SHG members trained under the Deen Dayal Antyodaya Yojana-NRLM have launched mustard and groundnut oil processing units in Rajasthan and Gujarat, creating both self-employment and community-level value addition infrastructure. These enterprise models, nurtured through extension handholding, simultaneously resolve the value-addition deficit and the rural employment challenge.

Strengthening Research–Extension–Farmer Linkages

Strong institutional linkages are the lifeblood of an effective extension ecosystem. The Research–Extension–Farmer (REF) continuum, where ICAR institutes generate knowledge, KVKs adapt and demonstrate it, and frontline extension workers deliver it to farmers, is the intended architecture of India's public extension system, but it frequently breaks down due to poor coordination, funding gaps, and bureaucratic compartmentalisation (ICAR, 2022).

ICAR institutes with oilseed mandates, ICAR-NRCG (groundnut), ICAR-DRMR (rapeseed-mustard), and ICAR-IIOR (oilseeds) generate a steady stream of improved varieties and production technologies. While KVKs serve as district-level technology hubs, validating these technologies under local agro-climatic conditions and provide training to both farmers and extension agents.

The ATMA framework, which facilitates convergence of public extension, NGO outreach, and private agribusiness at the district level, offers a blueprint for integrated extension delivery. When well-resourced and professionally managed, ATMA coordinates FLD demonstrations, processing training, and market linkage activities around a single target crop such as mustard or soybean, resulting in coherent district-level oilseed development programs rather than fragmented, scheme-wise interventions. State agricultural universities (SAUs), NGOs with community reach, and commodity-focused agribusiness companies must all be recognised as legitimate extension actors and engaged accordingly.

Bridging Research and Field Practices

The technology-yield gap in oilseeds, the chasm between what experimental stations achieve and what average farmers harvest, is real, persistent, and deeply damaging. In groundnut, for instance, research station yields routinely exceed 3,000 kg/ha while national average farm yields hover around 1,500 kg/ha. Closing this gap

requires not just better seeds and agrochemicals, but fundamentally better systems for knowledge co-creation and technology transfer.

Participatory Research and Innovation Platforms

Participatory Variety Selection (PVS) and Participatory Plant Breeding (PPB) have demonstrated that involving farmers directly in the identification and testing of oilseed varieties dramatically improves adoptability. In the drought-prone Bundelkhand region, collaborative research between JNKVV (Jawaharlal Nehru Krishi Vishwa Vidyalaya) agronomists and sesame farmers led to the identification and local spread of drought-tolerant sesame accessions that formal variety release channels had systematically overlooked because they did not fit standard evaluation criteria (Witcombe *et al.*, 1996). Such participatory research simultaneously builds farmer confidence in science, ensures ecological adaptability, and accelerates on-farm adoption.

Public–Private Partnerships and Scheme Convergence

The private sector brings market intelligence, supply chain infrastructure, and investment capacity that are lacking in public extension systems. Contract farming arrangements between edible oil processors and oilseed farmer groups, such as those piloted between Adani Wilmar and soybean producers in Madhya Pradesh, provide simultaneous benefits, i.e., guaranteed offtake and input support for farmers, and supply chain reliability for processors. However, such arrangements need regulatory oversight, transparent contracts, and extension support to ensure that power asymmetries do not systematically disadvantage resource-poor farmers.

Convergence of government schemes is equally vital. Linking NMEO-Oilseeds with PM-KUSUM (solar irrigation), the Soil Health Card initiative, PMFBY crop insurance, and e-NAM market access creates a comprehensive, supportive ecosystem. Block-level extension workers trained to navigate this convergence landscape, helping farmers simultaneously access improved seeds, soil health-based fertiliser recommendations, weather-indexed insurance, and digital market platforms that can generate far greater impact than any single scheme applied in isolation.

Future Prospects and Recommendations

The roadmap for sustainable oilseed development through strengthened extension is clear, though challenging. Several strategic priorities deserve urgent and sustained attention.

Revitalise the extension workforce:

Thousands of village-level extension worker (VLEW) positions lie vacant across India's states, and those in post are often under-trained, under-equipped, and demoralised.

Recruitment drives, competitive salaries, ongoing professional development, and performance-based incentives are non-negotiable prerequisites for an effective oilseed extension system (Swanson & Rajalahti, 2010).

Design climate-resilient extension programs:

Oilseed farmers face mounting climate risks, erratic monsoons, rising temperatures, and increased pest pressure that require extension advisories calibrated to local agro-climatic realities.

KVKs should be equipped as climate advisory hubs, offering drought-tolerant variety recommendations, conservation tillage guidance,

micro-irrigation facilitation, and contingency crop planning as integrated advisory packages.

Mainstream gender and social inclusion:

Gender-responsive extension, women extension agents, women-only training camps, SHG-linked advisory services, and recognition of women's contributions in official program records must shift from a marginal add-on to a core design principle.

Extension programs targeting tribal and SC/ST communities should be delivered through trusted community intermediaries, in local languages, and with culturally appropriate learning approaches (Pattnaik et al., 2018).

Leverage digital technologies at scale:

Hybrid extension models combining face-to-face farmer interactions with digital advisory platforms, WhatsApp-based farm advisory groups, AI-powered crop diagnostic apps in regional languages, and drone-based remote sensing advisories can dramatically expand the reach of a limited extension workforce. Digital literacy training for both farmers and extension agents is an essential concurrent investment (Mittal & Mehar, 2012).

Align extension with market realities:

Extension curricula and training programs for oilseeds must go decisively beyond agronomy to encompass post-harvest management, quality grading standards, price negotiation skills, FPO governance, and market intelligence. The goal should be to transform oilseed farmers from passive price-takers into active, street-smart agricultural entrepreneurs (Shepherd, 2007).

Conclusion

Agricultural extension remains the critical link that connects researchers, farmers, innovations, markets and institutions in the oilseed sector. The journey from field to market is not just about increasing oilseed production but also enabling an environment where farmers can be empowered with knowledge, institutions become responsive and markets are accessible. To achieve this, the extension system must produce professionals equipped not merely with agronomy knowledge, but with better market understanding, communication skills, gender sensitivity, and a deep commitment to the most marginalised oilseed farmer. The seeds of sustainable oilseed transformation have already been sown. With an extension ecosystem that is nurturing, adaptive, and farmer-first, they can grow into the abundant harvest that India so urgently needs for achieving both nutritional well-being and livelihood security.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine

Volume 04, Spcl. Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-35

UNEQUAL PROTECTION UNDER POLICY: THE SELECTIVE REACH OF PRICE SUPPORT ACROSS OILSEED CROPS IN TRIBAL ODISHA

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Abstract

India's Minimum Support Price (MSP) provides a base price for seven oilseed crops including both mustard and niger. However, in the tribal districts of Odisha, the same policy produces strikingly different outcomes for farmers growing these two crops. Using district level Farm Harvest Price data from the Directorate of Economics and Statistics, this article documents that mustard farmers across tribal Odisha consistently receive prices above MSP while niger farmers face significant income deficits below the announced support price despite identical policy coverage. This divergence does not stem from differences in government policy design but from a structural hierarchy of enforcement, where crops with commercial visibility and private market demand receive effective protection, and indigenous tribal oilseeds receive only announcements. The article examines this enforcement gap, its national implications for India's edible oil import dependency, and outlines ground-level actions required to extend genuine price support to tribal niger farmers.

Introduction

India's relationship with oilseeds is one of quiet contradiction. The country is among the world's largest producers of oilseed crops, spanning from mustard cultivation in the fields of the Indo-Gangetic plains to niger in the hills of the Eastern Ghats. Yet despite this abundance, India remains one of the world's largest importers of edible oil. The reason for this is not simply agricultural but institutional. The systems meant to support, protect, and incentivize domestic oilseed cultivation have not reached all farmers equally, and nowhere is this more visible than in the tribal hilly agro-ecosystems of Odisha.

Tribal region of Odisha occupies a distinct and ecologically significant position in the country's oilseed map. The forested, rainfed hilly tracts of districts like Koraput, Rayagada, Malkangiri, and Nabarangpur have sustained oilseed cultivation for generations, not as a commercial enterprise driven by market logic, but as a deeply integrated part of tribal livelihoods and food systems. Farmers here grow a range of oilseeds suited to the fragile ecology of marginal lands: crops that require low inputs, tolerate poor soils, and resist the uncertainties of rain-dependent farming. These are not the crops that dominate agricultural policy discussions in New Delhi, they are the crops that have historically existed at the margins of the formal agricultural economy, grown by communities that have themselves existed at the margins of state support systems.

The Minimum Support Price (MSP) is the government's way of protecting farmers from market failure. Announced annually for mandated crops including seven oilseeds, it represents a price support providing a guarantee that

regardless of what the market offers, the state stands ready to buy at a fair and remunerative rate. For decades, MSP has been the cornerstone of India's agricultural policy a nationwide price guarantees for every farmer and covered crop. On paper, that promise is uniform. It does not distinguish between a crop grown in Punjab and one grown on a hillside in Koraput. It does not acknowledge the difference between a crop with an established commercial processing industry and one sold exclusively through informal village markets. It treats all covered oilseeds as equals.

The ground, however, tells a different story. The effectiveness of MSP is not determined solely by the price announced it is determined by the infrastructure, institutions, and market forces that either enforce that price or fail to. Where procurement centers exist, where private buyers compete, where farmers know their legal entitlements, and where cooperative networks function as intended, MSP works. Where these conditions are absent, the announced price becomes a theoretical figure present in government circulars. In the tribal belts of Odisha, these two realities exist side by side, sometimes within the same district, sometimes between farmers cultivating different crops on similar land.

This article examines that divide using district-level Farm Harvest Price data from tribal Odisha to compare the actual market outcomes of two oilseed crops that share the same policy guarantee but inhabit entirely different institutional realities. Both have an MSP. Both are grown by tribal farmers in the same hilly districts. But as the data will show, only one farmer receives what the state promised.

Which raises a question that the numbers in this article will answer plainly: MSP for whom?

Mustard Dynamics: Market driven price stabilization

To understand why price support fails for some crops, we must first look at where it succeeds. In the agricultural policy discussions, Minimum Support Price (MSP) is framed as the support against total market crash. However, for mustard (Brassica juncea) growers in Odisha, the MSP operates less like a safety net and more like an invisible baseline that the actual market effortlessly outpaces.

Mustard is a mainstream, popular rabi crop deeply integrated into India’s edible oil market. Because of its predictable industrial demand from regional oil mills and an extensive network of private processing traders, market forces naturally drive the prices upward. Driven by the expansion of the rice fallow ecosystem in the tribal regions of Odisha, the highly resource-efficient mustard crop was integrated into this system, thus increasing its production in these tribal areas. As production increased, these tribal farmers were able to benefit from a robust institutional backbone: national procurement networks like NAFED (National Agricultural Cooperative Marketing Federation of India) maintain a strong physical and digital footprint through platforms like the e-Samridhi portal.

While a deep dive into the state's agricultural records shows that this trend has remained remarkably consistent over the years, if we look at a single year's marketing season; 2023-24 a highly favourable reality for the farmer emerges. In almost every single district, the Farm Market Price (FMP) did not just meet the government's price but also surpassed it.

Data from the district agricultural markets reveals that the farm gate price is highly favourable to the grower:

Table.1: Mustard Market Performance (Sales Season 2023-24)

District	Government MSP (₹)	Farm Market Price (FMP) (₹)	The Price Deficit (₹)
Koraput	5,650	6,050	+400
Mayurbhanj	5,650	6,539	+889
Nabarangpur	5,650	6,700	+1,050
Rayagada	5,650	5,733	+83

Source: Directorate of Economics and Statistics. (2025).

What this data reveals is a healthy, functioning value chain. In Nabarangpur, a mustard farmer walks away with an extra ₹1,050 per quintal beyond what the state guaranteed. In Mayurbhanj, the surplus stands at a staggering ₹889. The safety net works perfectly here precisely because the market is strong enough that the government rarely has to step in and buy the crop itself.

But this success story indicates a critical question: what happens when a crop has the same theoretical guarantee, but absolutely none of this commercial infrastructure? To answer this, we have to look at Niger (Guizotia abyssinica), locally known as Ramtil or Alasi.

The Niger Dilemma: A Paper Promise in the Tribal Hills

Unlike mustard, which is a mainstream commercial crop, niger is a minor oilseed crop which is often regarded as the "lifeline of tribal agriculture." Tribal agriculture in Odisha is mainly rainfed and situated in hilly terrains, and niger being highly climate resilient can grow easily. It is perfect for contingent cropping.

Because niger is considered a Minor Forest Produce (MFP) item, its procurement is not handled by national bodies like NAFED or NCCF. Instead, the responsibility is passed on to tribal cooperative networks like the Tribal Development Cooperative Corporation of Odisha Ltd. (TDCCOL) and local Large Size Agricultural Multipurpose Cooperative Societies (LAMPS) under the MFP scheme. Paradoxically, even though this crop technically receives benefits from both the high MSP and the MFP frameworks, actual government procurement remains dismally low. This breakdown stems from two compounding failures. Local cooperative agencies like TDCCOL and LAMPS are burdened by structural and operational constraints that prevent effective functioning, while the near or total absence of village level collection centers, leaves farmers with no practical alternative to the private traders who, facing no competition, dictate the prices entirely.

A Lok Sabha reply (Unstarred Question No. 445, Nov 30, 2021) revealed that state wise government procurement for niger seed in Odisha registered at zero and notably, mustard procurement through government agencies showed a similarly absent footprint. Yet mustard farmers still received above MSP prices, as shown in Table 1. The difference is not government intervention it is private market demand. Thus, while mustard farmers benefit from private competition and a solid market, niger growers face a total collapse of the state safety net.

When we look at the marketing season of 2022-23 across the exact same tribal districts, the data shows a devastating income deficit forced onto niger growers:

Table.2: Niger Market Performance (Sales Season 2022-23)

District	Government MSP (₹)	Farm Market Price (FMP) (₹)	The Price Deficit (₹)
Rayagada	7,287	4,000	-3,287
Nabarangpur	7,287	4,500	-2,787
Malkangiri	7,287	5,000	-2,287
Koraput	7,287	5,600	-1,687

* Source: Directorate of Economics and Statistics. (2024).

The contrast here is prominent. While a mustard farmer in Koraput pulls in ₹400 above the state guarantee, a niger farmer just across the same region is forced into a ₹1,687 distress sale below it, an especially bitter reality given that Koraput is widely considered "The niger hub of Odisha". In Rayagada or Nabarangpur, the situation is even worse; farmers are losing between 38% and 45% of their rightful income. They are forced to sell a crop worth ₹7,287 for as low as ₹4,000.

Just like mustard's success, a deep dive into the data from previous years like 2019-20 and 2021-22 shows that this trend is remarkably consistent. This is not a one-time bad harvest or a temporary market glitch. It is a chronic, structural failure where niger farmers are consistently left out of the formal pricing system year after year.

A Hierarchy of Neglect: Reason behind unequal MSPs

The glaring divide between the prosperity of mustard and the stagnation of niger is not an accident. MSP is not a single policy it is a spectrum of enforcement. At one side we have paddy and wheat, backed by the Food Corporation of India's guaranteed procurement infrastructure, political weight of major producing states, and decades of investment in storage and purchase centers. For these crops, MSP is effectively a guaranteed price. FCI's open ended procurement policy means a paddy farmer in Punjab knows before sowing that a government buyer will arrive at harvest. No oilseed farmer in tribal Odisha has that certainty. At the other end sits niger (minor oilseed), with a government notification announcing ₹7,287 per quintal and almost nothing on the ground to enforce it.

Mustard (major oilseed) sits somewhere in between. Private market demand and commercial oil mill networks have improved mustard farmer outcomes significantly, as the data in this article shows. But even this is fragile: rapeseed-mustard is currently the only major oilseed trading above MSP, while groundnut, sesamum and sunflower trade below support levels. Even among major oilseeds, MSP protection is fragile and market dependent. The difference between mustard and groundnut outcomes is not policy it is the degree to which private processing demand compensates for absent procurement.

This hierarchy directly harms the country and it is difficult to justify. Public procurement is largely limited to a few foodgrains such as paddy and wheat, while oilseeds receive far less institutional attention. As a result, India remains heavily import dependent, spending over ₹1.41 lakh crore on edible oil imports in 2021-22 alone.

The government's own NMEO-Oilseeds mission was launched precisely to fix this dependency. Yet simultaneously, India which ranks first globally in niger production according to a NITI Aayog report of August 2024, cannot guarantee its niger farmers even 55% of the announced support price. The country exports niger seed worth millions while the farmer who grew it received less than half its legal value. This is the central contradiction of India's edible oil economy a push for self-reliance at the national level built on a foundation of institutional neglect at the farmer level. The hierarchy of MSP enforcement is not incidental it is the structural reason why India's oilseed import dependency persists despite decades of price support policy.

The Way Ahead

The National Mission on Edible Oils Oilseeds (NMEO-Oilseeds), approved in October 2024 with an outlay of ₹10,103 crore, explicitly names niger among its target crops and commits to region-specific clusters in tribal and rainfed tracts. Odisha's own implementation plan proposes mini oil extraction units through Value Chain Partners and FPO linked seed distribution systems (Department of Agriculture, Odisha, 2024). These are the right institutional directions but some ground-level actions are essential to make them reach the tribal niger farmer. First, Dedicated Price Support Scheme activation for niger in KBK districts, with village-level collection points operational during the harvest window, is the most immediate need. Without a physical buyer within accessible distance, no price policy has meaning. Second, FPO led collective marketing can serve as a bridge while formal procurement infrastructure is being built aggregating niger output at the block level gives tribal farmers bargaining power they currently lack entirely. Third, MSP awareness campaigns in local languages, delivered before the harvest season rather than after, are the lowest cost intervention available because a farmer who does not know their legal entitlement of ₹7,287 per quintal cannot demand it.

Conclusion

In tribal Odisha, price support works for crops the market already values, mustard farmers receive above MSP prices because private demand substitutes for absent government procurement. Niger farmers face a 23% to 45% income deficit because neither government procurement nor competitive private demand has materialized for their crop. Same region, same policy, opposite outcomes. This is not a coincidence it is a predictable result of a system that builds enforcement infrastructure around commercially visible crops and leaves indigenous tribal oilseeds with policy promises and empty procurement registers. As long as MSP remains a number without an institutional mechanism to enforce it at the village level, it offers tribal niger farmers in Rayagada and Koraput no real protection.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine

Volume 04, Spcl. Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-36

TRANSFORMING THE TRIBAL AGRICULTURE THROUGH OILSEED VALUE CHAINS

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Abstract

Oilseed plants hold a very unique and strategic position in the agriculture and industrial economy of any nation. India, for instance, is one of the largest producers of oilseeds in the world. Yet, despite this vast potential this sector continues to face challenges such as low productivity, fragmented value chains, inadequate processing units, dependence on imports, and the list goes on.

We are finding solutions to these challenges by setting up Farmer Producer Organizations (FPOs), which enable collective bargaining and providing gender focused tools that empower female farmers to help achieve this goal. The government encouragement of agro based industries under initiatives like "Make in India", "Atmanirbhar Bharat" and NMEO-OP has further strengthened the ecosystem for employment generation in the oilseed value chain. Government schemes like the Integrated Scheme for Oilseeds, Pulses, Oil Palm, and Maize (ISOPOM), and National Food Security Mission (NFSM) for oilseeds, aim to enhance productivity, provide input subsidies, and promote post-harvest infrastructure. Through this, we can bridge the gap between laboratory yields and land outcomes. Using digital tools will speed up adoption and create a self-sustaining model for economic independence in rural areas.

Breaking chain from the fields to modern markets

The traditional agricultural marketing channel in remote tribal pockets is linear and economically exploitative in nature. Cultivators are structurally isolated; they have no warehouse infrastructure and are mostly under immediate financial pressure to sell their products in loss to village traders and unregulated brokers (artyas). Intermediaries exploit this lack of real time price discovery and transport options by purchasing raw goods at prices far lower than the Minimum Support Price (MSP) set by the government to sell them at huge profit margins in urban wholesale distribution hubs (mandis). To resolve this many small yet impactful measures can be taken such as:

The architecture of market led value chain system

A market led commercial strategy inverts the traditional agricultural lifestyle. Instead of managing production independently and then looking for a buyer, the entire cultivation process is guided from the outset by verified consumer demand, buyer quality requirements, and industrial processing needs. The flowchart (Figure 1) below illustrates the conceptual flow of a closed loop, market led oilseed value chain:

Figure 1: Conceptual Flow of a Closed-Loop Market-Led Oilseed Value Chain.



FPOs as Institutional Anchors

FPOs are the main vehicle through which these commercial arrangements are formalized to achieve vital cost efficiencies. FPOs buy certified seeds, soil conditioners and biopesticides directly from the manufacturers at bulk prices, bypassing retail distributors, thereby lowering the cost of inputs for members. FPOs can also aggregate their output and negotiate directly with national oil processing conglomerates, FMCG companies and state agencies to secure supply contracts, thereby completely removing predatory middlemen. Advanced FPOs set up local processing units such as automated seed cleaners, colour graders and oil expelling mills, allowing local communities to sell packaged filtered oils and high protein animal feed, keeping the financial margin within the local economy.

The Gender Revolution in Rural Agriculture

The adoption of advanced oilseed technologies is a highly disruptive social intervention in traditional rural production systems with patriarchal power relations and traditional land ownership.

Socio-Economic Integration and Livelihood Security

Moving from subsistence cereal production with low economic returns to a structured oilseed agribusiness enhances economic returns in many ways. Consistent cash generation mitigates involuntary seasonal migration; whereby rural youth leave villages during dry seasons to find informal work in urban areas. As it also improves the lifestyle of farmers, they can now afford a nutrient-dense diet of legumes, dairy and fresh produce, breaking a systemic dependence on high-interest moneylenders.

The Gender Dimension

Women are the sector's main workforce and supply up to 70% of the field labour needed for oilseed maintenance. They are actively in command of intensive tasks such as hand weeding, transplanting, manual harvesting and post-harvest winnowing. Despite this high contribution to the labour force, they are often downgraded to "unpaid family helpers" due to structural barriers they are unable to formalize their land registration, getting bank financing, or voting in cooperatives. Regional development plans must deliberately apply a gender transformative methodology to scale production models:

Reduced Drudgery: Introduction of specialized manual field equipment like hand-cranked groundnut decorticators and mechanical seed drills to reduce heavy physical strain and save valuable labour hours.

Financial Inclusion: Women's enrolment as independent FPO shareholders and routing of electronic commodity payments directly into their verified personal bank accounts.

Capacity Building: Training of the existing women's Self-Help Groups (SHGs) on operating small-scale processing units. When women manage local oil mills and control financial records, their voice in household financial allocations increases, leading to higher spending on family nutrition, healthcare, and educational materials.

Bridging the Gap from the Laboratory to the Land

Many new agricultural innovations are engineered in academic laboratories and have a hard time reaching the remote plots of smallholders due to institutional failures in communication. Top-down extension pathways always fail because they ignore the unique microclimates, soil variations, and real-world capital limitations faced by tribal farmers.

Participatory Action Research (PAR)

To overcome this structural mismatch, progressive extension frameworks use Participatory Action Research (PAR) methods where tribal smallholders are active research partners (Figure 2). The best mechanism is the FLD (Frontline Demonstration) conducted by regional Agricultural Science Centres and university agronomy departments on active smallholder farms. Instead of performance on corporate research plots, local communities see high-yielding, pest-resistant mustard strains grown right in their village boundaries with local water sources and realistic soil inputs. The peer-to-peer verification effect is powerful. When a community sees a neighbouring farmer increase total harvest volume by 40% to 60% through optimized nutrient applications and pure seed inputs, the adoption of these practices quickens and voluntarily spreads to neighboring villages.



Figure 2: Participatory Extension System

Institutional Mechanisms and the Yield Gap

The operational concept of "yield gap" measures the difference between the maximum biological yield that could be produced under ideal laboratory conditions and the actual volume of harvest recorded on a typical smallholder farm. To bridge this performance gap, multi-institutional cooperation is required:

- Building operational networks that link state agricultural ministries, traditional tribal councils, and grassroots non-governmental organizations (NGOs) to develop the cultural familiarity and trust necessary to operate effectively in unique tribal communities.
- Employing digital communication tools like voice-based mobile notifications, hyper local weather forecasting, and short, highly visual video guides produced in local dialects to deliver real-time guidance on pest outbreaks, fertilizer timing and spot market updates.

- Community Seed Banks Training regional production groups to manage self-sustaining community seed banks. Seed masters, cultivators' selection, preventative cleaning, and long-term storage from their own harvests, building long-term local resilience and guaranteeing a steady supply of acclimatized seeds.

Conclusion

Scaling modern oilseed technologies in tribal areas offers a pragmatic approach to tackle both rural poverty and structural food insecurity. For long term success, we need to move beyond short-term, disconnected subsidy programs to an integrated framework that links field-level production, technological upgrades, and downstream market linkages into a unified pipeline. Structuring isolated smallholders into professional and well-managed FPOs transforms agricultural development from a simple survival activity into an efficient commercial enterprise. Such market structures, coupled with gender specific resource policies, unleash the economic potential of women cultivators, resulting in broad community enhancements. At the same time, replacing old teaching methods with collaborative field-based action research ensures that scientific progress is realistic, affordable, and easily adopted by local communities. Given the rising demand for edible oils in the country, the development of far tribal areas into efficient, sustainable oilseed production areas builds an enduring blueprint for rural self-determination.

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GreenariA
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An Agricultural Monthly e-Magazine

Volume 04, Spcl. Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-37

EMPOWERING TRIBAL WOMEN FARMERS THROUGH BLOCKCHAIN AGRICULTURE

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Abstract

Across remote, hilly terrains, smallholder agricultural communities are undergoing a quiet, tech-driven revolution. For generations, traditional oilseed supply chains have systematically isolated tribal farm women, leaving them trapped as raw-material labourers while predatory middlemen and massive urban corporate processing plants drain away the real processing profits. This issue is magnified by stark land inequalities; in these rugged, isolated corridors, up to 80% to 86% of households are forced into practicing subsistence farming on hyper-fragmented, marginal plots measuring fewer than one to two hectares. To dismantle this barrier, a decentralized approach introduces solar-powered, community-owned cold-pressing mills right in the village clusters, allowing tribal women-led Farmer Producer Organizations (FPOs) to directly process value-added sesame and niger oils (Figure-1). By layering this physical network with secure digital tools including permissioned blockchain tracking and self-executing smart contract payouts the entire system transforms. It securely bypasses intermediaries and routes electronic retail payments directly back into the female farmers' digital wallets within seconds, dramatically mitigating traditional informational and market access.

However, realizing this high-tech agricultural model requires navigating several real-world limitations. While decentralized tech provides deep economic transparency, its rollout faces structural friction due to widespread final-mile internet dropouts, localized power outages, and high deployment costs in rugged, isolated landscapes. Furthermore, our focus remains firmly bound by space constraints; because this complete study is strictly limited to a concise 5-page editorial ceiling, certain deep technical explorations such as cross-chain interoperability protocols and advanced algorithmic smart contract code optimization-must be deferred to subsequent, dedicated research trajectories.

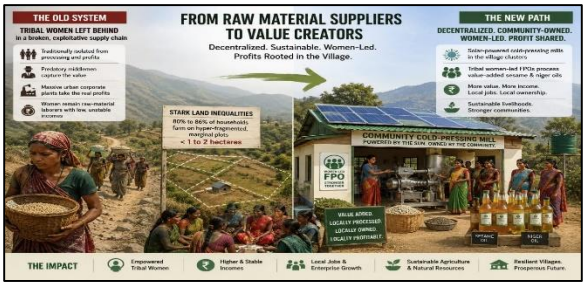


Figure 1: Empowering Tribal Women Through Decentralized Oil Processing

Institutional Framework: The Role of Tribal Women-Led FPOs.

Social Aggregation and Gender-Centric Governance.

In remote, topographically isolated terrains, tribal farm women comprise the core agricultural workforce, executing intensive manual cultivation and post-harvest preservation while carrying

heavy domestic burdens. Despite their critical contributions, structural barriers systematically isolate them from direct economic rewards. Geographically, these women are cut off from commercial hubs by rugged terrain and inadequate rural transport infrastructure, severely limiting their access to modern innovations, digital tools, and timely market extensions. This isolation breeds severe informational and capital deficits. Because training programs and digital platforms rarely account for local socio-cultural dynamics or high technology costs, tribal women remain dependent on long chains of local intermediaries who buy raw oilseeds at rock-bottom field-gate prices. Consequently, the high-margin revenues of processing and value addition exit the village ecosystem entirely, locking smallholder households into generations of economic stagnation.

Supply Chain Gaps in Traditional Oilseed Networks.

The traditional oilseed logistics processes entail a high level of post-harvest losses, have lack of traceability, and complex layers of intermediaries that erodes their profits. Smallholders need to be able to prove product quality or organic origin or else they are price-takers to large corporate refiners. The use of decentralized ledger frameworks can address the asymmetry in transparency facing supply chains, yet their deployment will be limited by local infrastructure bottlenecks, and high friction in the final mile.

Technological Architecture: Integrating Blockchain in Fragile Terrains.

Lightweight Permissioned Ledger Design.

It is almost impossible to deploy a standard, resource-intensive public blockchain in a remote hill terrain because of extreme bandwidth limitations, intermittent power, and low computational capacity. To overcome these constraints, a lightweight permissioned blockchain architecture has been incorporated into this framework especially for resource constrained agri-food systems. In contrast with public ledgers that incur substantial transactional costs and latency, a consortium or permissioned blockchain provides ledger validation rights only to vetted participants, allowing high throughput with low latency. The physical network is arranged in a hierarchical node structure, with heavy validating tasks assigned to central hubs (for example, FPO headquarters or regional processing facilities) that rely on Proof of Authority (PoA) or Raft consensus protocols. At the same time, local field collection centers operate on lightweight Simplified Payment Verification (SPV) client nodes that run on ordinary mobile devices. Additionally, the design takes advantage of a bi-storage "BlockChain + IPFS (Inter Planetary File System)" approach in an effort to deal the network congestion and sluggish cellular uploading speed. Extensive documentation, such as batch photos, geo-coordinates, and chemical purity certificates, is shifted to off-chain decentralized storage, meaning only small immutable cryptographic hashes will write to the main ledger to conserve bandwidth.

Step-by-Step Supply Chain Cryptographic Logging.

To guarantee the market integrity of premium hilly oilseed value chains, every physical transition from the farm gate to the end consumer is securely logged as a sequential cryptographic block, eliminating tracking gaps in fragmented networks. The process initiates when oilseeds harvested by tribal women farmers are delivered to FPO collection points, weighed, mapped via GPS to verify geographical origin,

and issued a serialized QR code or RFID tag. FPO managers then use mobile client nodes to log baseline metrics, such as moisture and cleanliness, sealing the dataset with the centre's private cryptographic key to establish an unalterable digital identity. At the cold-pressing facility, the transformation into bottled oil is recorded by logging milling timestamps, production yields, and hygiene compliance, directly linking the raw crop to the finished liquid yield. During mountain transit, shipping agents scan the QR codes at valley checkpoints to eliminate adulteration blind spots. Finally, the end consumer scans the on-bottle QR code, decrypting the ledger history to reveal a complete, auditable timeline proving the organic mountain origin from the tribal farm to the retail shelf.

Smart Contracts for Autonomous Financial Payouts.

Traditional agricultural value chains often trap smallholder farmers in predatory economic loops characterized by extensive payment delays and heavy reliance on local middlemen. By embedding self-executing smart contracts into the ledger architecture, the FPO system completely automates the transaction pipeline, executing pre-agreed business rules without human manipulation or third-party interference. Buyers register demand and lock required purchasing capital into a secure digital escrow contract. The moment digital delivery confirmation is logged on-chain such as an electronic signature or barcode scan at the central distribution warehouse the smart contract triggers instantly (Figure-2). The system then executes an autonomous financial split: the base commodity rate and the premium market surplus are calculated instantly and routed via direct-to-bank electronic transfers to the personal digital wallets of the tribal women cultivators.

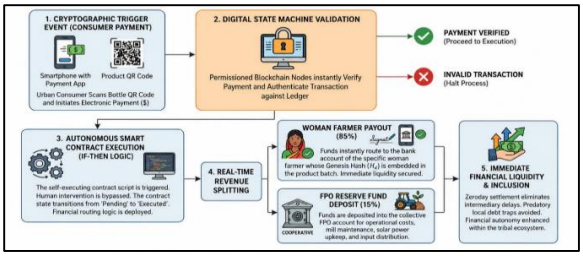


Figure 2: Decentralized Smart Contact Financial Payout.

Operating value chains through these decentralized smart contracts drastically lowers transactional friction, cuts administrative overhead, and completely shields vulnerable smallholder communities from arbitrary price exploitation by middle-tier brokers.

Socio-Economic Impacts and Market Dynamics.

Capitalizing on the "Hilly Niche" and Consumer Premiums.

Agricultural goods grown in isolated, high-altitude regions possess high value due to their pristine growing environments, traditional chemical-free farming methods, and rare nutritional profiles. However, when these commodities enter conventional, unverified markets, they are frequently mixed into low-grade bulk stocks, erasing their premium identity. Blockchain technology resolves this market failure by acting as an unalterable proof of provenance, allowing the FPO to isolate and aggressively market its "hilly niche". The immutable ledger functions as a powerful digital brand narrative, assuring health-conscious urban consumers that they are purchasing authentic, cold-pressed tribal oils free from synthetic adulterants. Because the blockchain establishes ironclad transparency, the FPO can command significant retail premiums, as modern consumers consistently demonstrate a higher willingness to pay for foods with verifiable origins, certified

safety standards, and documented ethical backgrounds.

Financial Autonomy and Gender Inclusion at the Grassroots.

Integrating blockchain networks directly with women-led FPOs triggers a structural shift in the socioeconomic dynamics of indigenous tribal communities. In traditional rural agricultural systems, tribal women perform the majority of manual cultivation, yet men typically transport the harvest to markets and retain full authority over cash income. Direct-to-farmer smart contract payouts fundamentally change this dynamic by depositing earnings directly into the personal bank accounts of female cooperative members, shifting financial control to those performing the physical labour. Beyond immediate financial inclusion, managing decentralized technology nodes, digital data wallets, and FPO governance builds strong technical and administrative leadership skills among tribal women. This accumulation of independent income leads to optimized social outcomes, as empirical studies verify that economic capital controlled directly by women results in higher household reinvestment rates toward children's education, family healthcare, nutritional security, and sustainable farm equipment.

Conclusion.

Integration of decentralized technology within high-quality hilly oilseed supply chains becomes a revolution from extractive traditional supply chains towards sustainable local ecosystems. By empowering tribal farm women to become creators of value instead of being raw material workers, this paradigm solves such problems as social segregation, unequal distribution of land, and predatory middlemen involvement. Application of a light-weight and permissioned blockchain technology designed specifically to solve serious infrastructure and connectivity issues guarantees 100% product provenance. At the same time, automation of money transfers through self-executing smart contracts provides liquidity by transferring higher retail consumer premiums directly into digital wallets of female farmers.While some advanced optimization procedures and inter-blockchain mechanisms need further investigation as future research directions due to editorial limitations, immediate socioeconomic effects of this solution are obvious. Empowering women who do the actual physical work financially creates grassroots leadership and improves general household conditions of families. Thus, by building community-owned infrastructure and using cryptographic logging technologies, this structure becomes an irrefutable source of trust. This paradigm demonstrates how digital technologies can be used successfully even on fragile terrains creating a sustainable way to highly profitable agriculture in indigenous communities.

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GreenariA
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Volume 04, Spcl. Issue (01), 2026
ISSN: 2584-153X
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FROM FIELD TO FUTURE: DIGITAL INNOVATIONS IN OILSEED FARMING

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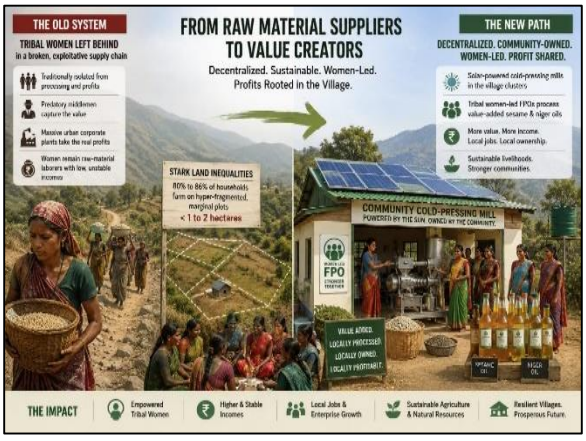


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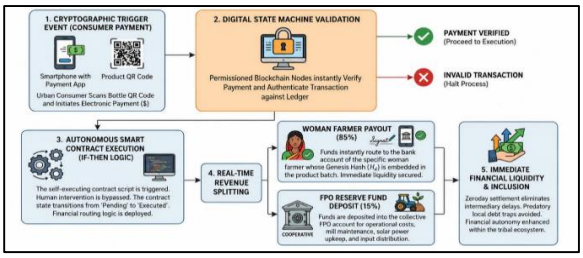


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GreenariA
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Volume 04, Spcl. Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-39

STRENGTHENING MARKET-LED OILSEED VALUE CHAINS FOR SUSTAINABLE TRIBAL DEVELOPMENT

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Abstract

Oilseeds are the most important agricultural commodities vital to global food security, economic stability, renewable energy & sustainable livelihood. With increasing demand for healthier vegetable oils & renewable resources, oilseeds have provided a vital economic lifeline for tribal communities. Despite significant production, farmers in tribal regions continue to receive a small share of the final market price due to poor infrastructure, weak value chains, less market information, *etc*. This paper aims to explore the strategies for strengthening market-led oilseed value chains through improved value addition, market access & policy support to promote sustainable livelihoods in tribal regions. This review shows that strengthening value chains through FPOs, processing units, e-marketing, farmer's market access, policy support results in improving farmer's welfare which leads to enhanced socio-economic resilience & sustainable livelihoods.

Keywords: Oilseed value chains, value addition, market access, policy support, sustainable livelihoods.

Introduction

Oilseed crops play a pivotal role in agricultural economy with its contribution to food security, nutritional wellbeing & livelihoods. India is the fourth largest oilseed producer globally, ranking behind the United States, China & Brazil. India is the third largest consumer of oil globally. Despite being one of the largest producers in the world the country remains one of the largest importers of edible oils because massive domestic demand consistently outpaces the limited supply. Tribal regions are best suited for cultivation of oilseeds due to their rich agro-biodiversity, climate, ecological factors & traditional farming techniques. The development of efficient oilseed value chains integrates production, storage, marketing, branding, and retailing while reducing post harvest losses thereby increasing profitability.

Oilseeds hold the second highest area and production value in Indian agriculture after cereals. In India 9 major oilseed crops are grown-groundnut (*Arachis hypogaea*), soybean (*Glycine max*), rapeseed-mustard (*Brassica sp*.), sunflower (*Helianthus annuus*), sesame (*Sesamum indicum*), safflower (*Carthamus tinctorius*), niger (*Guizotia abyssinica*), castor (*Ricinus communis*) & linseed (*Linum usitatissimum*) occupying 14.3% of gross cropped area & accounts for 8% of agricultural exports. India's oilseed production reached a mark of 42.609 million tons (MT) as of May, 2025. Despite this, nearly 76% acreage of oilseed cultivation remains rainfed, leaving yields at a high risk to agro-climatic fluctuations.

Strengthening value chains through FPOs, processing units, e-marketing, farmer's market access, policy support results in improving farmer's welfare which leads to enhanced socio-economic resilience & sustainable livelihoods.

An Overview of Oilseed value chains

An Oilseed value chain refers to the sequence or chain of activities and stakeholders involved in transforming oilseed crops from production to the final consumer while adding value at each stage. Market-led oilseed value chains give more priority to consumer demand & industrial needs over production based outputs.

Major supporting stakeholders in value chain include:

- Government departments & NGOs
- Agricultural universities, research institutes, ICAR institutions
- Banks, NABARD
- Digital agriculture & e-marketing platforms
- Private agribusiness firms

Challenges in tribal regions

Tribal regions have substantial potential for production of oilseed crops due to their rich agro-biodiversity but production is constrained by several factors like crops grown on depleting soils, deficiency of nutrition, lack of irrigation, *etc.* Approximately 64-76% of these crops is grown as rainfed and hence suffers from drought sometimes under erratic rainfall. It also suffers heavy loss due to low adoption of improved cultivars, modern technologies, and price fluctuations. The major challenges in tribal regions include: Low agricultural productivity; Production risks due to climate variability, diseases and pest infestation; Fragmented and small landholdings; Poor market access to tribal communities; Inadequate post-harvest infrastructure; Limited value addition structures; Unavailability of proper storage and processing units; poor transport facilities and connectivity in remote areas; exploitation by intermediaries; Weak farmer organizations and market linkages; Poor market knowledge and information; Policy and institutional constraints.

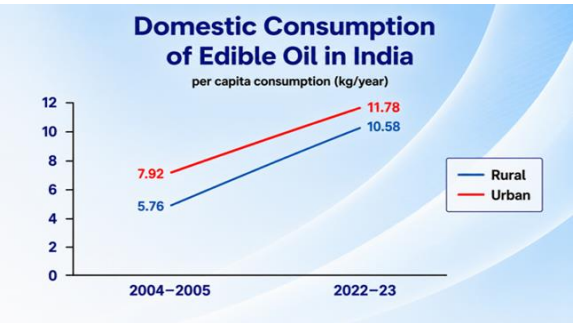


Figure. Rise in domestic consumption of Edible oils in India (Source: Niti Aayog)

Socio-economic integration

Socio-economic variables such as family size, gender, age, education level, land tenure status & occupation were significant factors influencing farmer's participation & performance in various agricultural activities.

Socio-economic integration is the process of linking or integrating tribal farmers and rural communities with broader markets, technology providers, processing industries and policy support systems. It encourages rural entrepreneurship, reduces poverty, and increases employment opportunities, promoting inclusive participation in value chains. Moreover women's participation in self help groups (SHGs) & farmer production organizations (FPOs) reduce gender inequality, strengthens financial inclusion and household welfare.

S. No.	Components of value chain	Major activities	Key stakeholders
1.	Input supply	Supply of quality seeds, fertilizers, farm machinery, irrigation equipments & advisory services	Seed companies, input dealers, research institutes, extension agencies, banks, govt. departments, NGOs
2.	Production	Land preparation, sowing, crop management, irrigation and nutrient management, harvesting	Farmers, Farmer producer organizations(FPOs), Self help groups (SHGs), Agricultural universities, KVKs
3.	Post-harvest handling	Cleaning, drying, grading, sorting, packaging, storage and transportation	Farmers, FPOs, cooperatives, ware house operators, storage unit agencies
4.	Aggregation & Procurement	Collection of produce, quality check, bulk procurement, market linkage	Traders, FPOs, procurement agencies, wholesalers
5.	Processing & value addition	Oil extraction, refining, packaging, branding, production of by products	Oil mills, food processing industries, agro- processing companies, packaging firms
6.	Marketing & distribution	Marketing, retailing, exports, e-marketing, logistics	Wholesalers, distributors, retailers, e-commerce platforms, transport agencies
7.	Consumption & feedback	Consumption, consumer analysis & market feedback	Consumers, food companies, hotels & restaurants

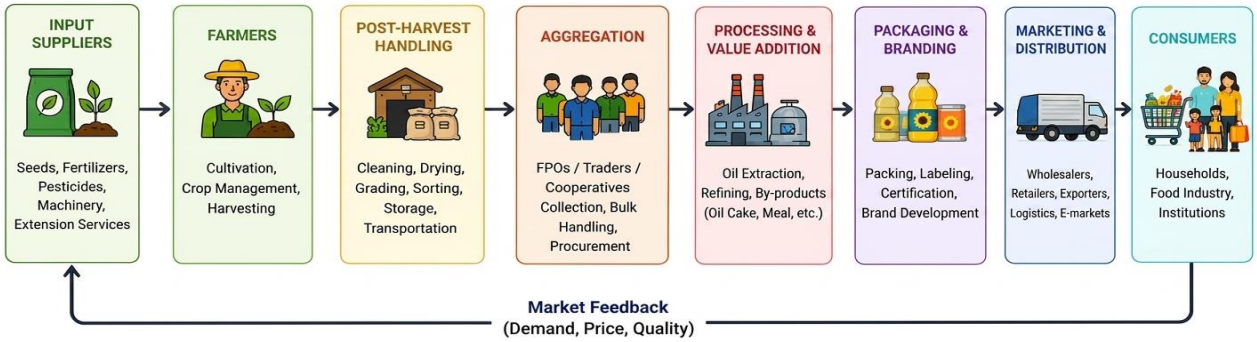


Figure. Flowchart showing components and stakeholders of a market-led oilseed value chain

Insights from recent reports on oilseed productivity in India

According to a recent report, Prime minister's "austerity" speech caught attention of public and markets when he urges to reduce the use of vegetable oils along with his appeal to save fuel, avoid buying gold for at least a year. This raises a question: Why is India, an agriculture-dominated economy, unable to produce enough edible oil for its own people?

On this issue, Dr. Himanshu Pathak, Director General of ICRISAT and former Director General of ICAR, says that India spends about Rs. 1.61 lakh crore (nearly $18.3 billion) every year to import around 15-16 million tons of edible oil annually because farmers see oilseeds as 'risky crops'. Erratic rainfall, pests, disease and unstable prices make oilseed crops less attractive as compared to rice & wheat. From an economic point of view, if we calculate the real cost of rice and wheat production, including water & electricity, oilseeds are more profitable. Dr. Pathak says, 'But policy support, insurance, free electricity and procurement still favors rice and wheat'. He adds that ICRISAT is working to boost production of oilseed and help the country become self- reliant'Atmanirbhar'.

Policy support

- Recognizing the strategic importance of edible oils, the government has launched the National Mission on Edible Oilseeds (NMEO-OS) in 2024, for 7 years up to 2030-31 to achieve self-sufficiency (Atmanirbharta) in edible oil production with a financial outlay of Rs.10,103 crores. It aims to bridge the gap between domestic production and consumption by promoting intercropping, expanding cultivation in fallow lands, and raising productivity through technology.

The cluster approach under NMEO-OS aims to accelerate the adoption of newly released crop varieties and recommended practices. Each cluster will be managed by a value chain partner (VCP) which can be a FPO, cooperative or public/private companies operating in oilseed sectors.

- To ensure timely availability of quality seeds, the mission introduces SATHI (Seed Authentication, Traceability and Holistic Inventory) portal enabling states to establish advance tie-ups with seed producing agencies, FPOs, government or private seed cooperatives.
- The National Food Security Mission (NFSM-oilseeds) supports productivity enhancement by promoting improved varieties of seeds, frontline demonstrations (FLDs) & farmer training programs.
- Market oriented policies such as National Agriculture Market (e-NAM) encourage transparent price discovery and direct market access to farmers reducing intermediary exploitations.
- Pradhan Mantri Fasal Bima Yojana (PMFBY) provides crop insurance to farmers against production risks.
- Policies to raise funds for establishment of small & medium scale oil processing units in tribal areas.



Future opportunities and Recommendations
Future prospects should focus on-

- Increasing productivity through climate resilient varieties, quality seed systems, and proper crop management practices.
- Establishing processing units, storage facilities and value addition enterprises in tribal areas.
- Adoption of digital technologies, AI-driven innovations, advisory services, e-marketing platforms.
- Using non-edible oilseeds as biodiesel, bio lubricants, bio plastics, *etc*.

Recommendations to strengthen oilseed value chain-

- Establishing district level seed hubs to promote adoption of high yielding, climate resilient oilseed varieties.
- Strengthen FPOs and SHGs by motivating women to facilitate value addition and better market access.
- Expand access to institutional credit, crop insurance for small and marginal tribal farmers.
- Strengthen agricultural extension work by providing training on post harvest management, mitigating crop losses, improving quality standards and value addition to farmers.
- Improves public-private partnerships involving government agencies, agribusiness firms and financial institutions.

Conclusion

Market-led oilseed value chains have the potential to transform traditional oilseed cultivation into a profitable and sustainable enterprise in tribal regions. This transformation massively depends on overcoming constraints such as low productivity, poor infrastructure, limited processing and storage units, lack of value addition units, weak market connectivity. Developing FPOs, expanding rural infrastructure, adopting digital marketing and climate smart technologies can significantly improves farmer's income and resilience. A well functioning market oriented value chain will strengthen India's oil self-sufficiency, promote sustainable growth, and maintain a long term national economic and food security. Integrating tribal communities into efficient value addition chains should remain a key priority for achieving sustainable livelihood and resilient agricultural development.

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GreenariA
Go Green, Learn Green
An Agricultural Monthly e-Magazine

Volume 04, Spcl. Issue (01), 2026
ISSN: 2584-153X
Article ID: G-26-sp1-40

MARKET-ORIENTED VALUE CHAINS, SOCIO-ECONOMIC INCLUSION AND EXPANSION OF OILSEED TECHNOLOGIES IN TRIBAL REGIONS OF INDIA

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Abstract

The tribal regions of central and eastern India contribute significantly to the production of minor oilseed crops, making up nearly 60% of the national output. Yet, these areas face challenges like low productivity, weak market connections, and limited household income. This paper examines how market-driven value chain methods, supported by agribusiness innovations, participatory research, and gender-sensitive support systems, can improve oilseed productivity and enhance rural livelihoods. Information from projects carried out in Madhya Pradesh, Chhattisgarh, Odisha, Jharkhand, and the North-Eastern states from 2018 to 2025 shows that stronger connections among Farmer Producer Organizations (FPOs), women's Self-Help Groups (SHGs), and private buyers can significantly boost farm income. Research indicates that household earnings from oilseed farming increased by 35% to 48% within three cropping seasons under these initiatives. The paper also points out institutional arrangements that could be included in national programs for broader implementation.

1. Introduction

Tribal districts in India grow crops like groundnut, sesame, niger, linseed, and other minor oilseeds under mostly rain-fed conditions. While these areas have suitable climates, average yields are still well below the national average, ranging from 0.6 to 0.8 t ha. The issues go beyond technological challenges and include poor market infrastructure, unequal access to resources, gender imbalances, and scattered extension services. As a result, the idea of market-led value chains shifts focus from production-only strategies to integrated systems that combine economic, social, and institutional factors.

2. Development of Oilseed Value Chains and Agribusiness Models

2.1 Production and Collective Marketing

Many tribal farmers have to sell their crops right after harvest, often getting prices 15 to 25% below the Minimum Support Price (MSP) due to a lack of storage and distress sales. Demonstration projects in Mandla district of Madhya Pradesh and Koraput district of Odisha united women-led SHGs under 22 FPOs, which collectively marketed about 4,200 tonnes of niger and sesame during 2023-24. Bulk buying attracted several edible-oil processors and increased farm-gate prices by ₹4 to ₹7 per kilogram.

2.2 Value Addition and Branding

Setting up decentralized oil expeller units with capacities of 5 to 10 tonnes per day helped cut post-harvest losses from 12% to around 4%.

Additional income came from using oil cakes for livestock and poultry feed. Marketing under the "Tribal Naturals" brand, along with Geographical Indication recognition for Koraput niger, allowed producers to fetch higher prices in specialized urban markets.

2.3 Market Linkages and Contract Farming

Collaborative efforts among FPOs, tribal development organizations, and private companies provided guaranteed procurement at prices above MSP by 5 to 8%, along with incentives for quality products. These arrangements helped nearly 1,850 households in Dantewada district of Chhattisgarh during 2024, leading to a 42% increase in yearly income from oilseed farming. Digital weighing systems, e-NAM connections, and traceability methods further boosted transparency and reduced the role of middlemen.

3. Socio-Economic and Policy Aspects of Oilseed Adoption

3.1 Gender Dimensions and Decision-Making

Even though tribal women carry out most of the fieldwork, only a small number have formal land ownership. Surveys from 2022 showed that women perform nearly two-thirds of sowing, weeding, and post-harvest tasks, while just 18% own land. Providing joint bank accounts and assigning 30% equity in FPOs to women's groups significantly raised their involvement in marketing decisions from 12% to 47%, resulting in better spending on education and household nutrition.

3.2 Livelihood Enhancement and Risk Reduction

Combining oilseeds with pigeon pea in intercropping systems increased cropping intensity from 110% to 165% in selected villages in Jharkhand. This diversification reduced seasonal migration and improved livelihood security. Additional activities like beekeeping and using oil cakes brought in extra annual income ranging from ₹8,000 to ₹12,000 per household.

3.3 Policy Support

Government programs, such as the National Mission on Edible Oils–Oil Palm (NMEO-OP) and the updated Rashtriya Krishi Vikas Yojana (RKVY), have dedicated resources for tribal districts. However, issues like delays in subsidy distribution, lack of gender-specific data, and poor institutional coordination still hinder implementation. New policy measures from Odisha and Chhattisgarh have highlighted women-focused procurement systems and mobile soil-testing services, showcasing effective collaboration.

4. Extension Approaches and Participatory Research

4.1 Farmer Field Schools and Variety Evaluation

Since 2019, ICAR–Indian Institute of Oilseeds Research and state agricultural universities have held Farmer Field Schools in various tribal districts. Participatory assessment of short-duration and drought-resistant varieties, such as NRCG-4 groundnut and PT-6 sesame, led to yield improvements of 22 to 31% compared to traditional varieties.

4.2 Community-Based and Digital Extension

Extension services delivered through mobile messaging in local languages reached nearly 48,000 farmers by 2025. These efforts increased the adoption of recommended crop management practices and planting schedules. Community Resource Persons trained under

DAY-NRLM became effective grassroots extension agents and received incentive-based support from FPOs.

4.3 Institutional Integration

An emerging three-level framework has shown promising outcomes. At the village level, SHGs and FPOs handle aggregation and basic processing. District-level Tribal Agribusiness Hubs support quality assurance, branding, and market access, while state-level value-chain cells coordinate research priorities, policy execution, and financial assistance. This institutional model is currently being tested in aspirational districts and may expand with future funding.

5. Case Study from Selected Tribal Regions

5.1 Mandla–Dindori Region, Madhya Pradesh

A partnership between the Madhya Pradesh State Cooperative Oilseeds Growers Federation, the Department of Tribal Welfare and ITC Limited helped create 14 women-led Farmer Producer Organizations. These organizations cover 6,800 hectares of land. Over three cropping cycles niger productivity increased from 0.52tones per hectare to 0.81tones per hectare. The use of contract pricing linked to e-NAM market rates gave producers a ₹6.2 per kilogram compared to local market prices. A survey of several farmers showed a 47% increase in income from oilseed cultivation and a reduction of one-third in seasonal migration. Because of these results the initiative has been expanded to Umaria district under the state-level Mission Oilseeds 2.0 program.

5.2 Koraput–Malkangiri Region, Odisha

The Odisha Tribal Development Cooperative Corporation worked with the Indian Institute of Oilseeds Research and private refining companies. Together they promoted the short-duration sesame variety GT-10 with procurement arrangements. Womens Self-Help Groups managed seed reserves and decentralized processing facilities. Evaluation in 2023–24 showed improvements. Sesame productivity rose by 28%. Womens involvement in marketing decisions increased from 14% to 52%. Average household earnings from oilseed cultivation grew from ₹19,800 to ₹31,400 annually. The "Koraput Niger" allowed producers to get higher prices in premium organic markets.

5.3 Dantewada–Bijapur Region, Chhattisgarh

Tata Steel and the Chhattisgarh Department of Agriculture introduced oil extraction units. These units operated in 37 villages with social responsibility funding. The intervention reduced -harvest losses from 14% to 3% and created jobs for 62 rural youth as machine operators. The area under contract farming expanded from 420 hectares in 2021 to 2,150 hectares by 2025. Women-headed households made up 41% of the beneficiaries.

6. Existing Constraints and Sources of Risk

Despite progress, several challenges continue to limit the effectiveness and expansion of oilseed value chains. Tribal women often face restricted access to land and finance, with low formal land ownership and limited access to loans and financial services provided by government for female-headed households. Inadequate infrastructure remains a major obstacle, as many tribal regions lack reliable roads to regulated markets and sufficient storage or cold-chain facilities. Poor teamwork among the several government organisations further hampers progress, with weak coordination among agriculture, tribal welfare, and rural development departments frequently causing delays in

program implementation and fund distribution. In addition, climatic and pest-related uncertainties such as rainfall variability and infestations like the leaf webber in sesame pose significant risks to yields under rain-fed conditions. Finally, price instability driven by fluctuations in international edible-oil markets undermines domestic price stability, makes the contract rules less reliable, and creates ongoing uncertainty for producers.

7. Emerging Innovations in Institutions and Technology

7.1 Digital Traceability Systems

The QR-code-enabled traceability platforms. These platforms improve supply chain transparency allowing buyers to verify crop origin, varietal identity and pesticide-residue standards. This system facilitated premium contracts with export-oriented processors serving markets.

7.2 Climate-Resilient Seed Networks

State seed corporations, ICRISAT and the Indian Institute of Oilseeds Research promoted decentralized seed multiplication through FPO-managed seed villages. They distributed varieties like ICGV 91114 groundnut and DNS-4 niger reaching about 9,200 tribal farmers during the 2025 kharif season.

7.3 Innovative Financing Mechanisms

NABARD introduced the Tribal Oilseed Value Chain Fund with a ₹1,250 crore corpus. This fund promotes investment in the sector with a first-loss guarantee mechanism covering 40% of risks. It encouraged banks and agribusiness enterprises to mobilize nearly ₹3,800 crore in private investment by early 2025.

8. Strategies for Large-Scale Expansion

- Creation of a National Traceability Framework: A digital platform integrating farmer databases FPO records and e-NAM transactions can improve transparency. It will enhance price discovery. Reduce information gaps throughout the value chain.
- Establishment of Integrated Tribal Agribusiness Centre: District-level centers with laboratories, branding facilities and market-linkage services should be developed with TRIFED. This will strengthen value-chain operations.
- Convergence with Existing Rural Development Programmes: Integration with schemes like PM-KISAN and MGNREGA can provide input support. It can also enable community-based investments in storage and processing infrastructure.
- Strengthening Research and Extension Linkages: Universities should support participatory breeding programs and gender-responsive extension activities. Regular interaction among researchers, extension personnel and FPO representatives will enhance technology dissemination and feedback.

Conclusion

The success of market-driven oilseed value chains in tribal areas relies on combining technological solutions with inclusive organizations that support gender equity, ensure fair prices, and strengthen ties between research and farming communities. Achieving the national goal of producing 45 million tonnes of edible oil by 2030 requires focused policy support and

innovative institutional solutions. Priority actions should involve increasing women's representation in FPO governance, integrating value-chain metrics into the Aspiring Districts Program, setting up specialized Tribal Oilseed Parks with shared processing facilities, and boosting agricultural universities' capacity to conduct participatory breeding and gender-responsive extension programs. With policy support and inclusive market mechanisms oilseed cultivation can drive sustainable agricultural development and socio-economic transformation, in tribal regions.

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