# GENOMICS-ASSISTED IMPROVEMENT OF OIL PALM: LINKING PRODUCTIVITY, PROFITABILITY, VALUE ADDITION AND IMPORT DEPENDENCE IN INDIA

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## ABSTRACT
India's oil palm strategy sits at the intersection of crop improvement, farmer returns, processing efficiency and edible-oil security. This study combines a national time-series analysis of domestic palm oil production and imports (2000-2024) with a focused synthesis of oil palm genetics and genomics to examine how genetic gain could contribute to productivity, profitability, value addition and lower import dependence. Domestic palm oil production increased from 40 thousand tonnes in 2000 to 305 thousand tonnes in 2024, while imports rose from 3.038 million to 9.400 million tonnes. For 2015-2024, the mean net domestic supply contribution was 2.98%, ranging from 2.20% to 3.51%, and it was 3.12% in 2024. Production remained at 305 thousand tonnes during 2022-2024, indicating a recent plateau. The genomic synthesis identifies four complementary leverage points: conservation and strategic use of genetic diversity; genetically verified dura x pisifera planting material; marker-assisted and genomic selection for complex yield, architecture and stress-response traits; and multi-trait improvement of oil quantity and quality. These approaches can raise fresh-fruit-bunch yield and oil recovery, reduce long-term losses from incorrect planting material, improve resilience and harvestability, and create scope for differentiated high-quality oils and more efficient processing. Their economic value, however, depends on conversion of genetic gain into field performance through locally validated breeding populations, suitable sites, reliable water and nutrition, certified nurseries, timely harvesting and nearby milling. Genomics therefore should not be treated as a substitute for agronomic readiness, but as a force multiplier within a coordinated Indian oil palm value chain. The study concludes that reducing import dependence requires simultaneous improvement in genetic quality, realized yield, farmer profitability, processing value addition and environmentally responsible expansion.

**KEYWORDS:** oil palm; Elaeis guineensis; genetic diversity; breeding; molecular markers; genomic selection; productivity; profitability; value addition; import dependence; India

## 1. INTRODUCTION
Oil palm (Elaeis guineensis Jacq.) is a perennial crop with exceptional oil productivity per unit land and produces both palm oil and palm-kernel oil for food, oleochemical and industrial value chains (1-3). For India, the strategic question is not simply whether planted area can increase, but whether each hectare can deliver more stable fresh-fruit-bunch (FFB) yield, higher oil extraction, reliable quality and acceptable farmer returns. Genetics and genomics are increasingly relevant to this objective because they can improve the biological potential of planting material before the long plantation cycle is locked into the field (2,4-10).

In oil palm, genetic improvement is essential due to a long juvenility period, perennial production, and large fields. Errors in selecting parent palm trees or in the quality of the seeds in oil palm may produce economic problems for many years. Genetic diversity associated with E. guineensis in Asia and the related American species E. oleifera provides potential yield and oil composition and represents alleles that can promote compact growth and adaptation to help overcome the tendency towards a narrow breeding base. Traditional methods of reciprocal-recurrent selection and crossing between duras and pisiferas will continue to be important, but the use of molecular tools for selection may greatly vary and increase the precision of selection. DNA information on the SHELL and VIRESCENS loci can directly improve the purity of the seeds and the management of harvesting.

There are multiple steps in the economic pathway from genotype to national supply. Higher number and weight of bunches, greater percentage of mesocarp, and higher oil-to-bunch ratio all increase oil palm yield per hectare. Compact architecture and easier depth-to-glide ratio may lower losses during harvesting. Genetic improvement to increase tolerance to abiotic factors such as drought and heat and biotic factors such as disease, as well as higher chain length and increased bio-element content of oil, may improve diversity and flexibility of end products. Genetic improvement, therefore, may influence profitability of oil palm plantations through greater yield and increased value of oil products.

For India, genomics-assisted improvement is especially relevant because the domestic industry is still expanding and decisions made in seed gardens and nurseries will shape future bearing plantations. ICAR-Indian Institute of Oil Palm Research studies have developed and validated SHELL-linked markers, whole-genome and genic microsatellites, and genome-wide associations for vegetative, bunch and oil-yield traits in diverse germplasm (11-17). These resources provide an Indian research base for stronger genetic traceability and pre-breeding. Operational deployment nevertheless requires validation in target Indian environments and careful management of genotype-by-environment interaction rather than direct transfer of marker effects from unrelated populations.

Though oil palm has the potential to be very productive, not all environments support successful oil palm cultivation. The success of an oil palm plantation is related to the distribution and intensity of rainfall, the presence of water deficits, temperature, the physical and chemical properties of soil, the age of the palm, the quality of the planting materials, and the management of the crop and harvesting operations. Even with an expansion in cultivated area, large yield gaps can remain (18-22). The challenges that oil palm cultivation presents to land use and biodiversity are the result of the displacement of natural ecosystems when oil palm plantations are established without proper environmental assessment (22-26). Specifically, for India, the main research concern is where oil palm cultivation will yield consistently, and how the cultivation systems can be managed to mitigate the ecological impacts that oil palm plantations will have on other cultivated areas.

India's import data suggest growing domestic edible oil demand and slow domestic oil production (23-25). Based on the available data, from 2000 to 2024, palm oil imports increased from 3.038 million tonnes to 9.400 million tonnes, while domestic production rose from 0.040 million tonnes to 0.305 million tonnes. The disparity highlights the inability to address thep circumstance of production through the trade, tariff, and supplier concentration analyses in isolation. These analyses must be coupled with a crop-science perspective to evaluate the potential of domestic production to fulfill a greater share of domestic needs and to apprehend the constraints to enhanced production.

Oil palm cultivation has a conditional potential that has been recognized by India. The second criterion in the re-evaluation of national potential of oil palm incorporated climate, soil, slope, land use and water (rather than assuming all land is cultivable) (26). The National Mission on Edible Oils-Oil Palm (NMEO-OP) has the same logic in supporting planting materials, nurseries, irrigation, tools for harvesting, and processing (27,28). These include the logistical and biological components of the crop. Oil palm has a multi-year immature stage and fresh fruit bunches have a limited storage period.

Recent statistics have documented growth in the cultivated area, production of fresh fruit bunches and crude palm oil, but have also documented concerns about production instability, demand for water, regional concentration, and the need for site-specific constraints (29). However, the long-term national production series have been seldom analyzed together with their net contribution to the availability of palm oil, from a perspective of crop development. The percentage growth may appear significant when the initial base is limited, but the absolute output may still remain small and the national dependence on the imported palm oil can still be significant. This is especially true when developmental targets are converted to investments.

## 2. MATERIALS AND METHODS

### 2.1 Study design, data sources and scope

The study employed an annual national time-series methodology with India as a unit of analysis. The period of focus was from 2000 to 2024, providing 25 data points for the analysis of domestic production and imports of palm oil. The study workbooks provided the series for production and imports. Metadata from the USDA Production, Supply and Distribution Database and FAOSTAT were consulted, and values were expressed in thousands of metric tons. The analysis maintained the distinction made in the original documents between aggregate national palm oil data and commodity-specific partner-country trade data, and partner-country concentration and tariff data were excluded from the analysis as they do not relate to the performance of the crop.

Export data for the years 2015-2024 were available, with the exception of 2018. In line with the source data, exports were small relative to imports and production. For the net-supply calculation, the missing 2018 export value was set to zero as an explicit analytical assumption. No data on stock changes were available. Estimated domestic availability of palm oil was calculated as production plus imports minus exports. This is a material balance estimate and should not be interpreted as the actual consumption of palm oil.

The crop-development interpretation was based on a structured evidence synthesis spanning eight linked domains: site and land suitability; genetic resources and breeding; planting-material identity and nursery quality; plantation establishment; water and nutrient management; support during the immature period; harvesting and FFB processing; and environmental monitoring. Peer-reviewed plant-science and genomics literature, ICAR-IIOPR research, national suitability assessments and NMEO-OP provisions were used to define these domains (1-17,26-32). No new field phenotyping, genotyping, association mapping or genomic prediction was performed in the present study.

**2.2 Genetics, genomics and value-chain evidence framework**

The genetics/genomics synthesis was organized into four layers. First, genetic-diversity and germplasm studies were used to assess the importance of conserving broad allelic variation in E. guineensis and E. oleifera. Second, major-gene and marker-validation studies were used to evaluate planting-material verification, particularly SHELL-based discrimination of dura, pisifera and tenera. Third, linkage mapping, GWAS and genomic-selection studies were reviewed for complex traits including bunch yield, oil yield, vegetative architecture and stress response. Fourth, oil-quality studies were used to connect genetic variation in fatty-acid composition, carotene content and post-harvest oil quality with value-addition potential (6-17,30-32).

Productivity, profitability and value addition were treated as linked outcome pathways rather than as directly measured farm-budget variables. Productivity pathways included FFB yield, oil-to-bunch ratio, oil yield per palm, resilience and harvestability. Profitability pathways included reduced losses from non-tenera contamination, more reliable yield, potential reductions in harvesting difficulty, and improved output per unit of fixed plantation cost. Value addition included improved oil composition, carotene content, lower free-fatty-acid potential and stronger processing quality. Evidence from non-Indian studies was used only to establish biological or economic proof-of-concept and was not transferred as an India-specific financial estimate (16,17).

**2.3 Statistical analysis**

Descriptive statistics were calculated for annual domestic production. The compound annual growth rate (CAGR) was calculated as

CAGR = [(X2024/X2000)^(1/24) - 1] x 100.

A linear model, Xt = a + bt, was fitted separately to production and imports, where b represents the average annual absolute change in thousand metric tonnes. Because annual agricultural and trade series may contain non-normal variation and influential years, monotonic trend was also assessed using the Mann-Kendall statistic and Sen's slope estimator (33,34). Statistical significance was evaluated at $p < 0.05$.

For 2015-2024, the import-dependency ratio was calculated as

Imports/(Production + Imports - Exports) x 100.

The complementary net domestic supply contribution (NDSC) was calculated as

[(Production - Exports)/(Production + Imports - Exports)] x 100

which is equal to 100 minus the import-dependency ratio. An NDSC value of 0 means that the domestic net output contributes a negligible share in the estimated availability. The import-to-production ratio was determined for 2024 as Imports/Production.

For the descriptive phase analysis, the series of production data was divided into four periods (with visible changes in the production data) as: 2000-2007, 2008-2013, 2014-2020, and 2021-2024. Mean production and end-of-phase production were calculated for each of the four periods. These four intervals were not treated as planned interventions for the purpose of this analysis. The analysis was performed in Python and used the libraries NumPy, SciPy, and Matplotlib. Figures were prepared in RGB color mode and 300 dpi resolution.

## 3. RESULTS

**3.1 Long-term domestic production trajectory**

Total domestic production of palm oil grew from 40,000 to 305,000 tonnes over the period from 2000 to 2024. The average growth rate during this time was 8.83%. From the fitted linear trend, average production grew by 14.15 thousand tonnes per year ($R2 = 0.924$; $p < 0.001$). Sen's slope estimated an annual increase of 13.95 thousand tonnes, and Kendall's tau was 0.93. The close agreement between the regression and non-parametric results indicates a strong, sustained upward trend rather than a pattern driven by only a few exceptional years.

Growth was uneven over time. Production remained below 50 thousand tonnes until 2009. Production reached 80 thousand tonnes in 2010 and 180 thousand tonnes in 2013; after 2017, it surpassed 250 thousand tonnes. Production was 290 thousand tonnes in 2021 and 305 thousand tonnes in 2022. The reported level did not change in 2023 or 2024. The most recent observations therefore indicate a production plateau (Fig. 1).

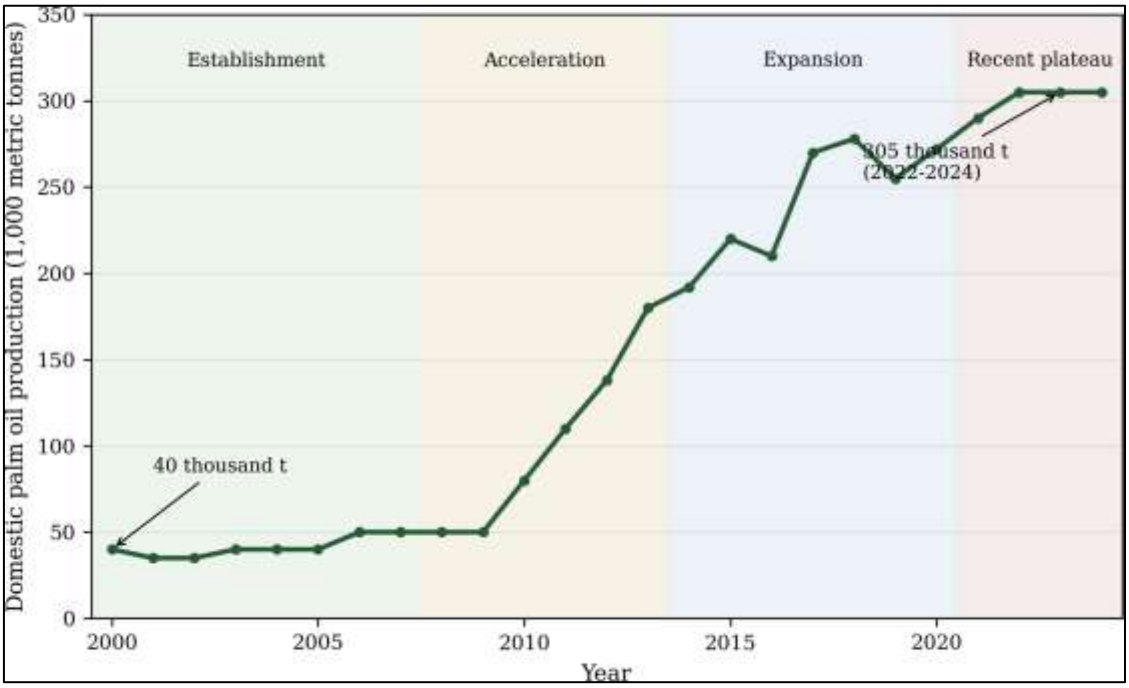

**Figure 1. Domestic palm oil production 2000-2024 with phases of production and development.**

The high percentage growth rate partly reflects the low starting level of production. In absolute terms, the fitted import trend was 324.65 thousand tonnes per year, which was about 23 times the domestic production trend. The two series are shown in separate panels in (Fig. 2) because their scales differ substantially. By 2024, imports were 30.8 times domestic production. These comparisons don't show the impact of imports on crop production. They show the extent of the domestic challenge of production.

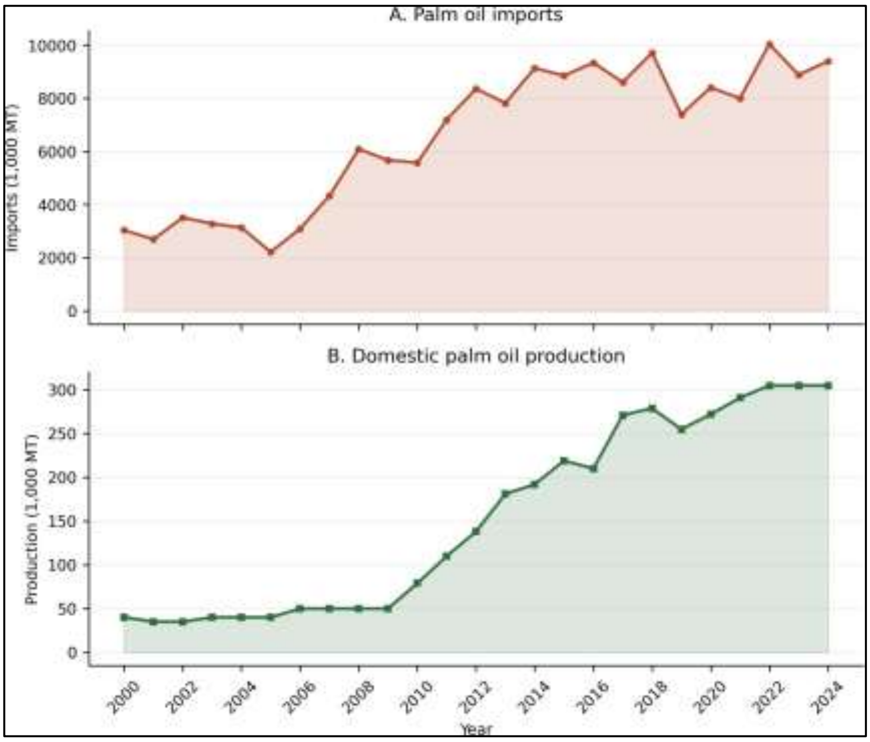

**Figure 2. India’s imports of palm oil and domestic production of palm oil, 2000-2024**

**3.2 Net domestic supply contribution**

The net domestic supply contribution (NDSC) showed little variation between 2015 and 2024. For that period, it reached a maximum of 3.51% in 2021 and a minimum of 2.20% in 2016, with an average of 2.98% (Fig. 3). In 2024, it stood at 3.12%. This shows that the increase in domestic palm oil production did not change the structure of the domestic component of the estimated availability of palm oil.

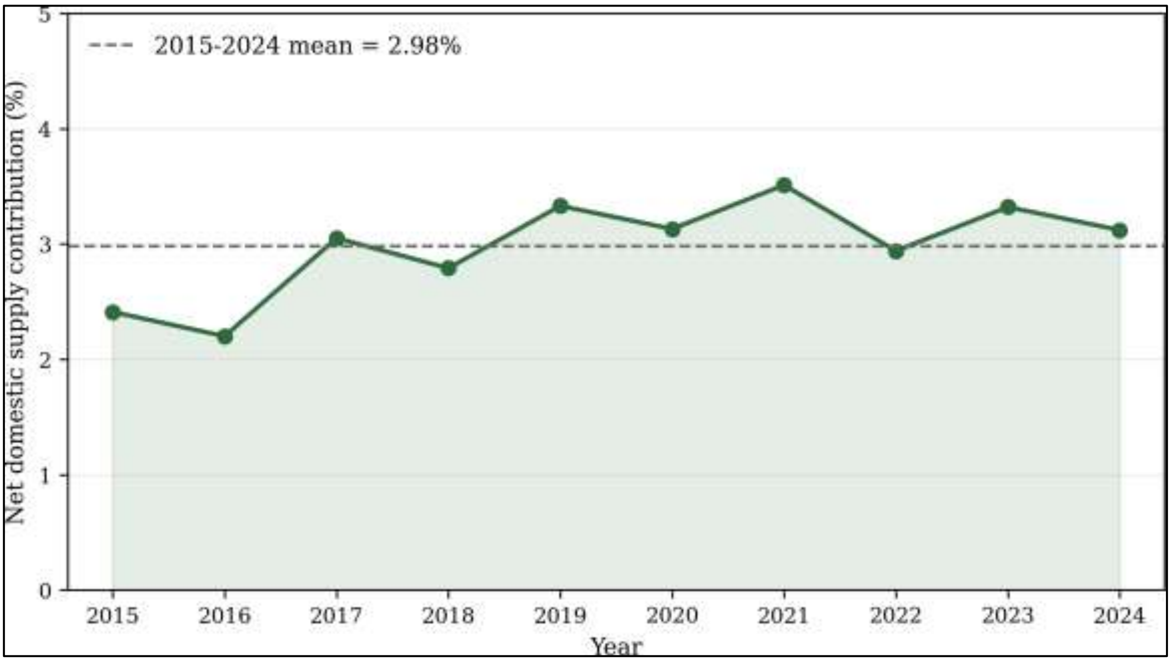


**Figure 3. Net domestic supply contribution to estimated palm oil availability 2015-2024.**

Within the context of the level of dependency, there was little change from year to year. The NDSC was greater than 3% in the years 2017, 2019, 2020, 2021, 2023 and 2024, but it was not on a continuously upward trend. The 2021 figure was the peak, with a fall in the 2022 NDSC despite a rise in domestic production from 290 to 305 thousand tonnes, as imports increased more rapidly. This demonstrates that crop output should be interpreted in the context of total supply rather than from year-on-year crop growth alone.

Because export levels were very low, the interpretation was insensitive to their inclusion. Thus the primary result is one of production inadequacy as opposed to production absence: India established a significant domestic oil palm industry, but net domestic production contributed only about 3% of the estimated availability over the last decade.

### 3.3 Production phases and agronomic readiness

The average domestic production for the periods 2000-2007, 2008-2013, 2014-2020, and 2021-2024 was 41.25 thousand tonnes, 101.33 thousand tonnes, 242.43 thousand tonnes, and 301.25 thousand tonnes, respectively (Table 1). During the first three periods, the end-of-phase figure increased from 50 thousand tonnes, to 180 thousand tonnes, and then to 272 thousand tonnes. The last period saw the figure increase to 305 thousand tonnes, which was only a 33 thousand tonne increase from the 2020 figure, and no increase was reported from 2022 onward.

**Table 1. Descriptive phases of domestic palm oil production, 2000-2024.**

| Period | Mean production (1,000 t) | End-of-phase production (1,000 t) | Production relative to phase import scale | Interpretation |
|---|---|---|---|---|
| 2000-2007 | 41.25 | 50 | 1.30% of mean imports | Establishment at a very small production base |
| 2008-2013 | 101.33 | 180 | 1.49% of mean imports | Acceleration in output, consistent with maturation of earlier plantings |
| 2014-2020 | 242.43 | 272 | 2.76% of mean imports | Expansion with interannual variation |
| 2021-2024 | 301.25 | 305 | 3.32% of mean imports | Higher output level but a plateau at 305 thousand tonnes during 2022-2024 |

This change from the establishment to the expansion phase of oil palm is understandable, considering the long juvenile period of oil palm and the need to align nursery, irrigation, and processing facilities. The recent stagnation indicates that larger planting-area targets may not, by themselves, produce corresponding increases in national output. In the absence of annual area and yield data, possible explanations for stagnation include the lag between new planting and bearing, yield limits in mature plantations, water and nutrient constraints, replanting needs, processing limitations, or a combination of these factors.

From the evidence synthesis, seven interrelated agronomic domains emerge (Table 2 and Fig. 4). Site suitability reflects whether temperature, rainfall, water deficit, soil depth, drainage, and existing land use can support productive crop growth. Production potential at establishment is influenced by the quality of planting material and nursery management. During the establishment and immature phases of crop growth, survival and future yield potential are influenced by soil conditions, moisture and irrigation reliability, nutrition, intercropping, and farmer support. During the bearing phase of crop growth, realized production is influenced by the condition of the canopy, the balance of nutrients, the water supply, pest and disease monitoring, the interval between harvests, and the rapid transport of fresh fruit bunches to the mills. Environmental assessment is necessary during all phases of crop growth.

**Table 2. Agronomic domains, principal risks and measurable indicators for responsible domestic oil palm development.**

| **Agronomic domain** | **Principal risk if neglected** | **Priority action** | **Measurable indicator** |
|---|---|---|---|
| Site and land suitability | Low yield, irrigation stress, erosion or habitat conversion | Overlay climate, seasonal water balance, soil depth, drainage, slope, existing land use and biodiversity risk before approval | Area approved after screening; water-source reliability; exclusion of protected and high-conservation-value areas |
| Genetic resources, planting material and nurseries | Narrow breeding base, incorrect fruit form, persistent low yield or non-uniform stands over a long plantation cycle | Conserve breeding diversity; use traceable D x P material; certify nurseries; cull abnormal seedlings; apply validated SHELL/identity markers and multi-location evaluation | Germplasm diversity metrics; seed-source records; marker-verified lots; fruit-form conformity; survival; multi- Location genetic performance |
| Establishment and immature phase | Mortality, delayed bearing, farmer withdrawal and poor future stand structure | Prepare soil, conserve moisture, manage weeds and ground cover, support irrigation and Intercropping during gestation | Survival at 12 and 24 months; age at first harvest; proportion of immature area maintained |
| Water and nutrient management | Reduced bunch initiation, lower bunch weight, nutrient deficiency and resource degradation | Use seasonal water budgets, efficient irrigation, leaf and soil testing, balanced fertilization and residue recycling | Water applied per hectare; leaf nutrient status; soil organic matter; yield response |

| Agronomic domain | Principal risk if neglected | Priority action | Measurable indicator |
|---|---|---|---|
| Crop health and plantation management | Yield loss from pests, diseases, Poor canopy condition or ageing palms | Regular surveillance, sanitation, integrated management and timely replanting plans | Pest/disease incidence; missing palms; palm-age profile; replanting area |
| Harvesting and FFB processing | Overripe or unripe bunches, delayed collection, low oil extraction and farmer losses | Set harvest intervals, collection routes and mill catchments before expanding area | Harvest rounds per month; hours from harvest to mill; rejection rate; oil extraction rate |
| Environmental monitoring | Unrecognized impacts on water, soil, biodiversity and neighbouring land uses | Establish baselines and monitor cumulative effects throughout the plantation cycle | Groundwater trend; soil erosion; pesticide use; land-cover change; compliance with exclusion zones |

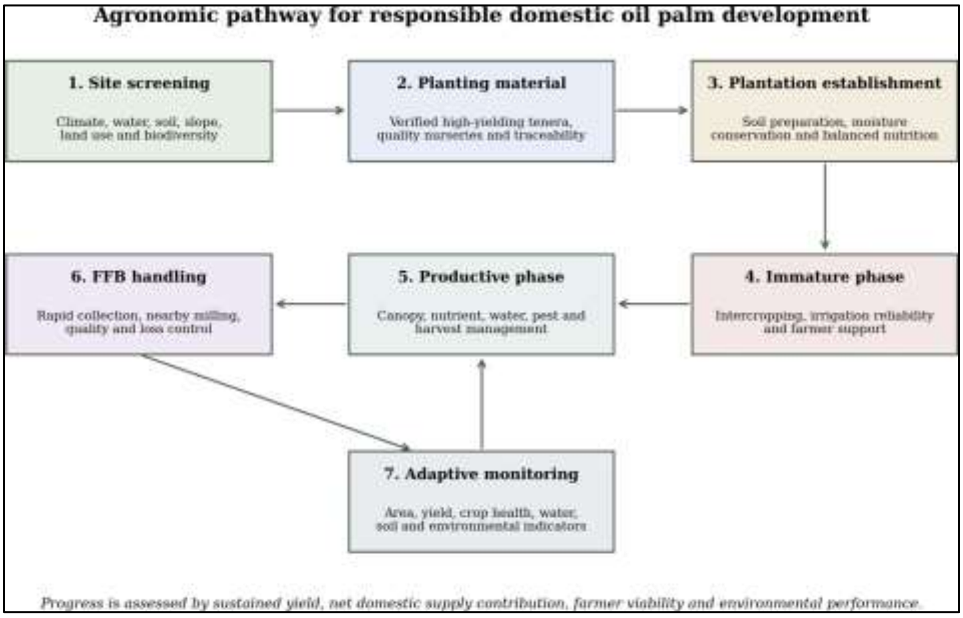

**Figure 4. Integrated pathway for responsible oil palm development in India.**

### 3.4 Genomics-assisted improvement pathways

The evidence synthesis identified a sequence from genetic resources to national supply (Table 3). Genetic diversity is the starting resource because sustained gain requires access to differentiated alleles for yield, architecture, adaptation and oil quality. Marker-based seed verification is the first operational checkpoint: the commercial objective is not merely to distribute seedlings, but to distribute genetically correct, traceable and vigorous D x P material. Indian marker work on the SHELL trait demonstrates that molecular verification can be incorporated into domestic breeding and nursery systems (6).

**Table 3. Genomics-assisted levers linking genetic improvement with productivity, profitability, value addition and import dependence in India.**

| Genetic/genomic lever | Primary target | Productivity pathway | Profitability / value-addition pathway | Relevance to import dependence |
|---|---|---|---|---|
| Diverse germplasm and pre-breeding | Allelic diversity, adaptation, oil quality | Broadens sources of yield and resilience alleles | Maintains long-term selection response and enables differentiated oils | Supports sustained genetic gain rather than one-time area expansion |
| SHELL-based genetic verification | Correct dura x pisifera / tenera identity | Avoids low-oil or sterile off-types in production fields | Prevents long-term sunk costs from incorrect planting material | Raises effective oil output from each planted hectare |
| GWAS and marker-assisted selection | Yield components, architecture, quality loci | Improves selection precision for validated traits | Targets traits linked to harvestability, oil recovery and quality | Accelerates deployment of alleles that raise domestic output |
| Genomic selection | Polygenic yield, oil yield and resilience | Predicts breeding value earlier and can shorten selection cycles | Potentially increases genetic gain per year and reduces field-testing of weak candidates | Speeds delivery of superior planting material if locally calibrated |
| Stress-response genomics | Drought, heat, salinity, disease resilience | Stabilizes yield under variable environments | Reduces risk of severe low-yield years and protects plantation returns | Improves reliability of domestic supply from suitable sites |
| Oil-quality and multi-trait breeding | Fatty acids, carotene, FFA, yield | Combines oil quantity with quality | Enables refining efficiency, product differentiation and premium value chains | Increases value captured domestically per tonne of palm oil |

For complex traits, GWAS and genomic selection provide complementary functions. GWAS identifies marker-trait associations and candidate genomic regions, whereas genomic selection combines genome-wide marker information to predict breeding value without requiring every favorable locus to be individually known. Indian studies have identified associations for leaf area, rachis length, dry matter, bunch and oil-yield traits, while international oil palm studies demonstrate useful genomic prediction for yield components (6-10,14,31,32). The principal advantage for a perennial crop is earlier and more information-rich selection, which can increase genetic gain per unit time when training populations are representative of the target breeding population.

A second pathway concerns value rather than volume alone. Natural diversity in fatty-acid composition, carotene concentration, free-fatty-acid behaviour and FFB yield provides material for multi-trait breeding of oils with improved nutritional or processing characteristics (17). In India, such traits could support value addition if breeding targets are coordinated with mill segregation, quality testing and downstream markets. Therefore, the genomics contribution to import substitution should be judged not only by hectares planted but by genetically attributable gains in oil yield, yield stability and saleable oil quality.

## 4. DISCUSSION

### 4.1 Strong relative growth but limited production adequacy

This study distinguishes between the national supply adequacy and relative growth. A growth rate of 8.83% over 24 years I do believe would qualify as accelerated growth, in that period production increased from 40,000 to 305,000 tonnes. In the absolute domain, the import trend fitted to the data would be roughly 23 times greater than the domestic production trend. This meant that the net domestic supply contribution was around 3%. This is important for crop development as it indicates the amount of production needed to change supply adequacy, as opposed to relying on a growth rate.

The recent stagnation should not indicate that oil palms in India have reached a biological hindrance. Production of oil palms depends on yield of bearing area and loss during harvest and post-harvest. Unfortunately, these elements cannot be completely separated in the production series of the country and hence serve as a stagnation alert. The oil palms development progresses through establishment, maturation, bearing and eventual replanting. Once the initial establishment is complete, focus is then on productivity and optimum production. A sustained pace of planting area is then a misleading production indicator, in case palms are immature, sites are of poor quality or no infrastructure to support the milling of the harvest is available.

Yield-gap research indicates that factors such as planting material, stand establishment, nutrient and water management, pollination, pests, harvesting, and the age of the plantation, among others, limit attainable oil palm production (1-3). For India, the implications are direct. Both new and established plantations must achieve stable bunch yields and oil recovery to increase the NDSC. Monitoring should therefore distinguish planted, surviving, and bearing areas and should report fresh-fruit-bunch yield, crude palm oil yield, oil-extraction rate, and the proportion of fruit processed within an appropriate time threshold.

### 4.2 Genetic diversity, breeding and planting-material quality

One of the first and most consequential plantation decisions is the genetic quality of planting material. Because oil palm is a long-term investment, a seedling that is low yielding, genetically misidentified or poorly adapted can depress returns for a substantial portion of a plantation cycle. Commercial D x P breeding exploits the SHELL locus to generate thin-shelled tenera palms with a greater mesocarp proportion and oil potential than dura. Indian development and validation of a CAPS marker for SHELL provides a practical basis for integrating fruit-form verification into seed-garden and nursery quality control (5,6).

Genetic quality is not synonymous with a single high-yield genotype. Maintaining diversity within E. guineensis breeding pools and strategically using E. oleifera and other differentiated germplasm can broaden the allelic base for future selection and provide sources of compactness, oil-quality variation and adaptation (2,11,12,17). Narrowing diversity too quickly can raise short-term uniformity while reducing long-term response to selection. A national improvement program should therefore combine elite recurrent populations with characterized germplasm banks, pedigree control, molecular fingerprints and multi-environment phenotyping.

Beyond major genes, most economically important traits are quantitative. High-density SNP and SSR maps, genotyping-by-sequencing and GWAS have identified loci associated with mesocarp oil content, vegetative traits, bunch components and oil yield (7-9,14,30). These discoveries are useful for trait dissection and marker-assisted selection when effects are sufficiently robust. For polygenic traits, genomic selection is more scalable because it predicts the aggregate breeding value from genome-wide markers. Oil palm studies report useful genomic prediction for yield components, while also showing that accuracy depends on population relatedness, trait heritability, marker density and training-set design (31,32). For India, prediction models should therefore be trained or recalibrated with Indian breeding populations and target environments rather than imported as fixed equations.

### 4.3 Genomic selection, resilience and accelerated genetic gain

The long breeding cycle of oil palm makes time a major economic variable. Conventional evaluation requires years of field observation before parents can be confidently selected, whereas genomic selection can rank candidates earlier using genome-wide relationships and marker effects. Its value is greatest when early selection shortens the interval between breeding cycles without sacrificing prediction accuracy. This can increase annualized genetic gain and reduce the land and time devoted to testing weak candidates, although genotyping costs and training-population maintenance must be included in deployment decisions (31,32).

Genomics also extends the breeding target from maximum yield under favourable conditions to yield stability. Transcriptomic research has identified oil palm genes responsive to drought, salinity and heat, illustrating the molecular diversity available for stress-response research (15). For India, where expansion includes environments with seasonal water constraints, stress-related markers or genomic breeding values should be evaluated together with physiological traits, water-use data and multi-location yield. Selection for resilience can protect profitability by reducing the frequency and severity of low-yield years, but only when validated under the actual target environment.

### 4.4 Productivity, profitability, value addition and import dependence

The primary economic reasoning is that genetic gain must result in saleable oil per hectare and cost per unit increasing. Increasing the yield of FFB and proportion of mesocarp along with an improved oil-to-bunch ratio and oil extraction yield all hold the potential for greater revenue. Palms that are more compact, fruit that is predictably ripe, and palms that are more stress tolerant can minimize harvest loss and production variations. Molecular technology that verifies fruit form obviates the sunk cost of producing seedlings of palms with non-fruit or fruit with poor quality. An SHELL test has the potential for substantial economic value for the Malaysian palm oil industry by eliminating non-tenera contaminant; these monetary estimates likely do not apply to India. However, the establishment of pre-planting genetic quality assurance shows evidence of profitability in India (16).

Value addition provides a second route to competitiveness. Breeding for favourable fatty-acid profiles, carotene content, lower free-fatty-acid tendency and stable oil quality can improve refining efficiency or support differentiated food and industrial uses (17). These benefits require a matching value chain: mills must preserve fruit quality, measure oil characteristics and, where justified, segregate specialized material. Import dependence can therefore decline through a combination of larger domestic oil volume and higher value captured from each tonne. Genomics contributes only when elite genetics are multiplied at scale, planted on suitable sites, managed to realize their yield potential and connected to efficient processing.

The second major limiting factor is water. Oil palm reacts to the distribution of rainfall and to the cumulative deficit of water rather than the total rainfall of a given year. Studies on water relationship and land suitability indicate that a long term deficit can hinder growth of vegetation and the development of flowers leading to a reduction in bunch yield. This is also influenced by soil depth and drainage as well as the site's topography (35,36). India's suitability assessment applied related criteria across contrasting climates and land types (26). Thus, the expansion of oil palm plantations should be limited to a defined seasonal water balance, reliable water sources for irrigation, an assessment of the soil's water retention capacity, and competing demands for water. Efficiency can be improved through measures such as drip irrigation and rainwater harvesting, but management cannot fully compensate for a site that is fundamentally unsuitable. Nutrient management must be site-specific and related to expected yield. Oil palm plantations lose large amounts of potassium and nitrogen, among other nutrients, in harvested bunches. Generalized fertilizer application can leave deficiencies uncorrected, waste inputs, and increase environmental impacts. An integrated approach to plantation management comprises balanced fertilization, residue recycling, ground cover, and leaf and soil analysis. Given the effects of nutrient and moisture stress, recommendations to farmers should consider the age of the palms, soil, rainfall, and estimated yield, as opposed to location, per se (1,3,37).

There is a period of immaturity that causes a lag between an investment and its return. Decreasing the risk that palms will be abandoned before fruiting can be accomplished through the application of the NMEO-OP provisions (27,28) for support of irrigation, maintenance and intercropping. Once palms begin bearing, harvest intervals and mill proximity become critical because fresh fruit bunch quality deteriorates rapidly after harvest. Expansion of plantations without nearby milling capacity can result in greater losses and poorer returns to farmers. Thus, the development of nurseries, planting, roads, collection centers, and milling facilities should be coordinated within each designated production area.

**4.5 Responsible expansion and environmental safeguards**

Although oil palm can produce oil at a high yield per hectare, land-use impacts depend on what land cover or production system oil palm replaces and on how plantations are managed. Oil palm's expansion into natural forests, high-conservation-value ecosystems, or water-stressed environments can cause biodiversity and ecosystem impacts without necessarily delivering proportionate gains toward the country's supply goals (18-22). Conversely, improving yields on existing plantations and carefully screening development on already cultivated land can reduce pressure for further expansion.

Land use "suitability" includes both physical and operational factors. A land parcel may be within the right temperature range and have the right soil type, but may be operationally unsuitable if the land is fragmented and irrigation is unreliable or there is no mill within close range to receive bunches. The national reassessment and international land-suitability research similarly integrate climate, soil, slope, land use, protected areas, and water constraints (26,36). Such assessments should be updated periodically because water constraints and future climatic suitability may differ from historical conditions (38).

Environmental safeguards should be defined through measurable indicators. Baseline conditions, including current land use, crops, water, soil, and biodiversity, should be recorded before planting. Subsequent monitoring will address irrigation, soil condition, vegetation and other environmental components. Our principal scientific goal is to improve the reliability of domestic oil palm supply with a minimum environmental impact, at prescribed sites.

**4.6 Limitations and scope of inference**

The study has five main limitations. First, the national production series do not incorporate annual planted area, bearing area, plantation age structure, FFB yield or oil extraction rate, so production changes cannot be decomposed into area and productivity effects. Second, annual national data hide interstate variation in climate, soil, irrigation, management and processing. Third, production and import series rely on secondary data and commodity definitions may differ or be revised. Fourth, the analysis is descriptive and does not estimate causal effects of imports, prices, tariffs or policy on planting decisions. Fifth, the study contains no farm-level cost-return data, seed-source records, pedigree information, fruit-form frequencies or genomic identities; therefore, profitability effects and the contribution of genetic gain to the national production trend are interpreted as evidence-based pathways rather than directly estimated impacts.

These limitations define the next research agenda. State-level monitoring should link planted and bearing area with certified seed source, parentage, fruit form, marker-verified identity, FFB yield, oil extraction rate and plantation age. Breeding trials should report genotype x environment performance across major Indian production zones, and genomic-selection models should be evaluated prospectively rather than only by cross-validation. Economic studies should then connect genetic class or predicted breeding value with establishment cost, annual management cost, harvest cost, FFB revenue, oil recovery, quality premiums and risk. Such integrated datasets would allow India to quantify genetic gain in rupees per hectare and in tonnes of avoided imports rather than treating genomics as a stand-alone laboratory output.

## 5. CONCLUSION

India's domestic palm oil production increased from 40,000 tonnes in 2000 to 305,000 tonnes in 2024, but net domestic supply contribution averaged only 2.98% during 2015-2024 and was 3.12% in 2024. Production also remained at 305,000 tonnes from 2022 through 2024. These figures show that rapid percentage growth from a small base has not yet produced structural adequacy in national palm oil supply. The production gap therefore requires higher realized oil yield per hectare in addition to carefully screened expansion.

The next phase should embed genomics within crop-performance management. Priority actions are to conserve and characterize breeding diversity; use certified D x P material; apply validated SHELL and identity markers in seed and nursery systems; develop GWAS-informed and genomic-selection pipelines for yield, compactness, resilience and oil-quality traits; and test elite material across Indian environments. These genetic gains must be supported by site suitability, irrigation, nutrition, immature-period support, harvest discipline and mill access. Only the combination can convert breeding value into farmer profitability and national oil output.

Genomics-assisted improvement allows for a shift in focus from crude volume to value. Developing varieties with advanced yield of oil, desirable composition of fatty acids, content of carotene and improved post-harvest quality, among others, would enable the production of differentiated palm oil and products while making palm oil processing more efficient. Use of certified planting material will prevent loss that usually occurs due to the use of sub-standard planting material. In the context of India, genetic gain will lead to higher productivity in palm oil, protection and enhancement of profitability, creation of value addition, and significant reduction in import dependency. Though imports of palm oil may still be necessary, genetic gain should be the primary focus, along with the recovery of oil from mills, the value incorporated into domestic oil processing, and an increase in India's share of the world palm oil supply.

**Declarations**

**Data availability:** The annual analysis in this manuscript relied on the study workbooks and publicly available USDA Production, Supply, and Distribution database and FAOSTAT. The cleaned analytical data set may be provided as supplementary material and is available from the corresponding author on reasonable request.

**Ethical approval:** Not applicable. The study used aggregated secondary data and did not involve human participants, animals or experimental plant material.

**Acknowledgements**

The author sincerely acknowledges the invaluable guidance, constructive criticism, and continuous encouragement provided by the Chairman and Advisory Committee members throughout the study titled "Global Research Trends in Cassava Value Chain, Processing, and Value Addition: A Bibliometric Analysis and Systematic Literature Review." Their insightful suggestions significantly contributed to the conceptualization and completion of this research. The author expresses gratitude to the institutional library and research facilities for providing access to relevant databases, scholarly articles, and reference materials essential for this study. The support extended by farmers, traders, processors, and and other stakeholders in the study area is also gratefully acknowledged for sharing their practical knowledge and field-level insights. The author further extends sincere thanks to peers, colleagues, and mentors for their r continu continuous support, encouragement, and valuable discussions, which have greatly enhanced the quality and rigor of this research work.

**Authors' contributions**

Dhayalan E-Article collection, Analysis and Interpretation
Indumathi V M- Contributed by developing ideas, validating and reviewing the manuscript
Prahadeeswaran M - Drafting
Parveen S - Reviewing
Radha M - Validating

**Compliance with ethical standards**

**Conflict of interest:** Authors do not have any conflict of interests to declare.
**Ethical issues:** None

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