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Research Article

Phenotypic diversity and characterization of indigenous tamarind (*Tamarindus indica* L.) germplasm in the semi-arid Marathwada region of Maharashtra

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ABSTRACT

This study presents the systematic morphological and pomological characterization of indigenous tamarind (*Tamarindus indica* L.) germplasm across the Marathwada region of Maharashtra, India. Executed over a two-year window spanning 2024 to 2026, extensive field surveys across the eight semi-arid districts of the region led to the identification and *in situ* evaluation of 48 distinct, wild, seedling-origin genotypes (6 representative selections per district). A total of ten vegetative and reproductive characters were recorded using standardized international UPOV and IPGRI descriptors to evaluate localized phenotypic diversity.

The germplasm exhibited extensive polymorphism, reflecting high genetic heterozygosity. Among the tree vegetative architectural traits, a semi-spreading growth habit (39.58%) and an irregular canopy shape (31.25%) occurred with the highest relative frequencies. Crucially, a profound dominance of sparse foliage (64.58%) and tall tree stature (58.33%) was recorded, outlining an evolutionary morpho-physiological adaptation to mitigate transpirational water loss under the high temperature and moisture-stress profiles typical of the central Maharashtra plateau.

Pomological characterization revealed substantial quantitative variations in reproductive traits, offering significant scope for commercial selection. Pod shapes were predominantly falcate (54.17%), while pod length and pod weight ranged widely from 7.2 cm to 16.5 cm and 11.2 g to 34.8 g, respectively. The fresh pulp recovery percentage—the primary economic indicator for commercial processing—varied from a baseline of 28.5% up to an elite 46.8%. Notably, genotypes MHD/NDD/T-1 (Nanded) and MHD/CSN/T-2 (Chhatrapati Sambhajinagar) emerged as outstanding elite ideotypes owing to superior pulp yield configurations and physical pod properties.

Ultimately, these findings confirm that the wild tamarind populations of Marathwada are a valuable genetic reservoir. The characterized collection provides an essential baseline for clonal multiplication trials, conservation efforts, and future selection-based breeding programs aimed at deploying high-yielding, climate-resilient cultivars for dryland agro-forestry systems.

Key words: *Tamarindus indica* L., Germplasm characterization, Marathwada, Phenotypic polymorphism, Pulp recovery, Semi-arid adaptation, Clonal ideotypes.

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Abbreviations

- **UPOV:** International Union for the Protection of New Varieties of Plants (Union Internationale pour la Protection des Obtentions Végétales)
- **IPGRI:** International Plant Genetic Resources Institute
- **PPV&FRA:** Protection of Plant Varieties and Farmers' Rights Authority
- **DUS:** Distinctness, Uniformity, and Stability
- **MHD:** Marathwada (Regional Genotype Prefix)
- **CSN:** Chhatrapati Sambhajinagar district identifier
- **JLN:** Jalna district identifier
- **PBN:** Parbhani district identifier
- **HNG:** Hingoli district identifier
- **NDD:** Nanded district identifier
- **BED:** Beed district identifier
- **LTR:** Latur district identifier
- **DHR:** Dharashiv district identifier
- **T:** Tamarind genotype selection tracker
- **cm:** Centimeter
- **g:** Gram
- **%:** Percentage
- **N:** Total population sample size
- **n:** District-wise sub-sample size

Introduction

Tamarind (*Tamarindus indica* L.) is a member of the Fabaceae family, with its name originating from the Arabic phrase "Tamar-ul-Hind," historically translated as the 'Date of India'. The tree is highly adaptable, flourishing across a wide geographical layout that spans multiple subtropical and semi-arid tropical zones. From a taxonomic standpoint, the genus *Tamarindus* is classified as monotypic, given that *T. indica* stands as its sole representing species. Depending on the linguistic and cultural landscape, it goes by various common vernacular names, including imli, chinch, amli, amlika, pult, tamarin, tamarindo, and tamarindier [1].

Classified within the Fabaceae family under the subfamily Caesalpiniaceae, tamarind (*Tamarindus indica* L.) carries a somatic chromosome number of 2n = 24 [2]. The name itself traces back to the Arabic phrase "Tamar-E-Hind," translating directly to "Date of India." Highly regarded for its fruit and quality timber, its sprawling canopy also makes it a favored choice for roadside shade and avenue planting. Although its evolutionary origins point to tropical Africa, the tree has naturalized across global tropics and subtropics, seeing extensive cultivation today in Southeast Asia, the Americas, and Australia [3].

In India, the crop is primarily integrated into the rainfed farming systems of states like Karnataka, Madhya Pradesh, Bihar, Chhattisgarh, Gujarat, Andhra Pradesh, and Tamil Nadu. On the global stage, market supply is heavily dominated by India and Thailand, where the sour cultivar accounts for a staggering 95% of total world output. India boasts a robust history of exporting processed pulp to Western economies; annual trade to the United States alone surpasses 10,000 tonnes, bringing in approximately 100 million Indian rupees [4]. With an active cultivation footprint exceeding 59,000 hectares and a yearly yield hovering around 200,000 metric tonnes, India firmly retains its status as the world's largest tamarind producer [5].

Characterized as a massive evergreen or semi-evergreen tree, tamarind delivers substantial therapeutic value due to a robust nutritional matrix packed with essential vitamins, minerals, antioxidants, and dietary fiber [6]. The fruit pulp stands out for its high concentration of ascorbic acid, thiamine, iron, calcium, and phosphorus, while also carrying secondary metabolites like flavonoids and polyphenols that drive its potent anti-inflammatory and antioxidant actions [7,8]. Because virtually every component of the tree including the pulp, seeds, leaves, and pericarp is loaded with these free-radical scavengers, they serve as excellent organic alternatives to synthetic antioxidants. Naturally, the precise layout of these chemical constituents shifts based on regional soil traits, localized weather patterns, and geographic positioning.

The seeds contain targeted bioactive agents capable of exerting anticancer, antimicrobial, and antispasmodic effects. Within the pulp itself, key antioxidants like catechin, taxifolins, and succinic acid operate alongside tannins, which provide notable antiulcer and antibacterial protection [9,7,8]. Its characteristic tartaric acid functions simultaneously as a natural laxative, antimicrobial agent, and antioxidant. Furthermore, anti-inflammatory terpenoids run through the plant framework, while the foliage synthesizes specific protective compounds like vitexin, isovitexin, and naringenin.

These varied biochemical dynamics explain why different plant parts feature prominently in traditional medicine to manage ailments like jaundice, diarrhea, and hemorrhoids [10,11]. For instance, a simple aqueous infusion of the leaves mixed with a pinch of salt is a classic home remedy for clearing coughs and treating liver disorders. Beyond medicine, the fruit is a staple flavor enhancer utilized globally in juices, savory sauces, preserves, pickles, and confectionery. It remains nature's richest source of tartaric acid, making it an indispensable culinary acidulant [12]. Scaled commercial cultivation of this crop is becoming increasingly vital to satisfy the rising global market demand for plant-based therapeutics and natural derivatives.

A major bottleneck in advancing tamarind breeding programs is the historical scarcity of research on critical morphological traits, which are fundamental for systematic germplasm classification and cultivar management [13]. To protect native populations from genetic degradation and fully leverage premium germplasm for crop enhancement, it is vital to screen for elite genotypes featuring superior horticultural characteristics. Securing these high-performing lines demands systematic, ex-situ clonal preservation across India's diverse ecological gene banks [14].

To prevent genetic erosion and fully exploit premium germplasm for crop enhancement, it is necessary to identify elite localized genotypes based on desirable horticultural and economic traits. Addressing this crucial gap, our research focused on the systematic characterization of 48 distinct indigenous tamarind genotypes across the eight semi-arid districts of the Marathwada region in Maharashtra. By evaluating ten essential vegetative architectural features and reproductive pod attributes—including canopy configurations and fresh pulp recovery percentages—this study aims to enhance the commercial value of tamarind as a resilient cash crop, providing a sustainable agro-forestry framework to support rural economies on the Maharashtra plateau. Our investigation evaluates phenotypic frequency distributions and geographical performance mapping to assess the genetic variability of native tamarind populations across the semi-arid Marathwada plateau. By examining ten key traits across 48 distinct genotypes—spanning vegetative tree architecture, physical pod dimensions, and industrial pulp recovery percentages—this work highlights the most distinctive phenotypic markers and isolates outstanding regional ideotypes. Ultimately, this baseline documentation is designed to guide future clonal multiplication and targeted breeding strategies aimed at maximizing economic yield and climate resilience in dryland horticultural systems.

Materials and Methods

Experimental Site and Agro-Climatic Conditions

The study was conducted across the Marathwada region, situated in the southeastern part of Maharashtra, India. The region is characterized by a tropical, semi-arid climate with an average annual rainfall ranging between 500 mm and 800 mm, primarily received during the southwest monsoon. The typical temperature ranges from 20^0C to 41^0C, making it an ideal eco-geographical zone for studying the resilience and diversity of indigenous tamarind (*Tamarindus indica* L.) populations.

Survey and Germplasm Collection

A comprehensive and systematic random survey was carried out across all the eight districts of the Marathwada region to identify distinct, wild, and seedling-origin tamarind genotypes. The extensive field surveys and germplasm collections were executed over a two-year period spanning from Jan-2024 to Jan-2026.

A total of 48 elite and distinct genotypes (6 representative genotypes from each district) were selected and coded based on their collection locality:

- **Chhatrapati Sambhajinagar (Aurangabad)** (MHD/CSN/T-1 to T-6)
- **Jalna** (MHD/JLN/T-1 to T-6)
- **Parbhani** (MHD/PBN/T-1 to T-6)
- **Hingoli** (MHD/HNG/T-1 to T-6)
- **Nanded** (MHD/NDD/T-1 to T-6)
- **Beed** (MHD/BED/T-1 to T-6)
- **Latur** (MHD/LTR/T-1 to T-6)
- **Dharashiv (Osmanabad)** (MHD/DHR/T-1 to T-6)

Morphological Characterization

In situ morphological characterization was performed on fully mature, healthy trees during their active vegetative and reproductive phases. Six key qualitative tree morphological characters were observed, recorded, and categorized:

- **Growth Habit:** Categorized into *Spreading*, *Semi-spreading*, and *Upright*.
- **Canopy Shape:** Documented as *Dome*, *Oval*, *Irregular*, *Circle*, *Semi-circle*, or *Cone*.
- **Foliage Type:** Classed visually as either *Sparse* or *Dense*.
- **Tree Stature:** Recorded based on tree height indices as *Tall*, *Medium*, or *Dwarf*.
- **Branching Habit:** Classified into *Erect*, *Semi-erect*, *Drooping*, and *Semi-drooping* patterns.
- **Leaf Color:** Evaluated using standard color profiles as either *Dark green* or *Light green*.

Standardization Framework: The morphological evaluations were strictly standardized according to established international and national descriptors for tamarind, including the International Union for the Protection of New Varieties of Plants (UPOV, 1987)[21] guidelines, the International Plant Genetic Resources Institute (IPGRI, 1991)[23] criteria, and the localized DUS test guidelines formulated by Singh et al. [22] via the Protection of Plant Varieties and Farmers' Rights Authority (PPV&FRA).

Statistical Analysis

The collected qualitative phenotypic data were subjected to frequency distribution analysis. Relative proportions and percentage distributions for each of the six morphological traits across the 48 genotypes were calculated and visually represented using distribution charts to assess the phenotypic diversity index of Marathwada's native tamarind germplasm.

Result:

Morphological and Pomological Characterization

In situ characterization was performed on fully mature, healthy trees during both their active vegetative phase and peak fruiting phase. The evaluation included ten comprehensive traits divided into tree architecture and reproductive pod parameters, strictly standardized according to the International Union for the Protection of New Varieties of Plants (UPOV, 1987)[21], IPGRI (1991)[23], and Singh et al. (2017) [22] guidelines:

- **Tree Vegetative Characters:** Growth habit (*Spreading, Semi-spreading, Upright*), Canopy shape (*Dome, Oval, Irregular, Circle, Semi-circle, Cone*), Foliage type (*Sparse, Dense*), Tree stature (*Tall, Medium, Dwarf*), Branching habit (*Erect, Semi-erect, Drooping, Semi-drooping*), and Leaf color (*Dark green, Light green*).
- **Fruit/Pod Characters:**
  - **Pod Shape:** Visually classified into *Straight*, *Falcate* (curved), and *Strongly curved*.
  - **Pod Length (cm):** Measured from the stem-end to the apex of 20 randomly sampled mature pods per genotype using a digital vernier caliper.
  - **Pod Weight (g):** Evaluated by weighing 20 representative pods using a high-precision electronic scale.

- **Pulp Percentage (%):** Calculated by extracting the fresh pulp from a known weight of pods, excluding the shell, fiber, and seeds, using the formula:

$$\text{Pulp Percentage (\%)} = \left(\frac{\text{Weight of clean pulp}}{\text{Total pod weight}}\right) \times 100$$

Pod Morphological and Quantitative Variations

The reproductive characters analyzed across the 48 genotypes showed substantial phenotypic variability, which is highly advantageous for targeted clonal selection programs.

- **Pod Shape:** The indigenous tamarind populations showed three distinct pod shapes. Falcate (curved) was the most dominant trait, present in 54% of the genotypes, followed by Straight (31%) and Strongly curved (15%).
- **Pod Length and Weight:** Pod lengths varied significantly, ranging from a minimum of 7.2 cm (MHD/PBN/T-3) to a maximum of 16.5 cm (MHD/CSN/T-2). Pod weight showed a closely corresponding distribution pattern, fluctuating between 11.2 g and 34.8 g. Heavy, long-pod genotypes were found centered primarily within Chhatrapati Sambhajinagar and Nanded districts.
- **Pulp Percentage (%):** As a primary economic indicator for industrial value, pulp recovery percentage varied from 28.5% up to an elite 46.8% (MHD/NDD/T-1).

Despite its importance, the limited knowledge in this area poses challenges to effective germ plasm management. Documenting morphological traits is critical for improving tamarind varieties in breeding programs [15,16]. The study revealed significant trait variation across genotypes, underscoring the influence of genetic diversity in selecting cultivars suited to specific purposes [17,19]. Additionally, preferences for com mercial cultivation are reflected in changes in growth habits, such as upright, semi-spreading, and spreading kinds; semi-spreading forms make harvesting easier [18]. Similar to this, differences in the color of the trunk bark and characteristics of the foliage, like the size, shape, and apex of the leaves, offer important information for choosing cultivars, with some attributes showing climatic tolerance [19,20,16].

Regional Adaptability Insights

Genotypes exhibiting falcate (curved) pod geometry coupled with intermediate pod weights were consistently observed in the hyper-arid districts of Beed and Dharashiv. This configuration may assist in optimizing internal moisture allocation within the pod chamber during prolonged drought conditions—a typical adaptive mechanism to the severe moisture deficits characteristic of the central Maharashtra plateau.

S.No.	District	Germplasm Code	Growth Habit	Canopy Shape	Pod Shape	Pod Length (cm)	Pod Weight (g)	Pulp Recovery (%)
1	Chhatrapati Sambhajinagar	MHD/CSN/T-1	Semi-spreading	Irregular	Falcate	12.4	22.5	38.2%
2	Chhatrapati Sambhajinagar	MHD/CSN/T-2	Upright	Oval	Straight	16.5	34.8	44.5%
3	Chhatrapati Sambhajinagar	MHD/CSN/T-3	Semi-spreading	Dome	Falcate	10.8	18.2	35.0%
4	Chhatrapati Sambhajinagar	MHD/CSN/T-4	Spreading	Circle	Curved	9.5	15.1	31.2%
5	Chhatrapati Sambhajinagar	MHD/CSN/T-5	Upright	Irregular	Straight	14.2	28.6	41.0%
6	Chhatrapati Sambhajinagar	MHD/CSN/T-6	Semi-spreading	Semi-circle	Falcate	11.5	20.4	36.8%
7	Jalna	MHD/JLN/T-1	Upright	Oval	Straight	13.8	27.2	40.5%

8	Jalna	MHD/JLN/T-2	Semi-spreading	Irregular	Falcate	11.2	19.5	35.8%
9	Jalna	MHD/JLN/T-3	Spreading	Dome	Curved	8.9	14.0	29.5%
10	Jalna	MHD/JLN/T-4	Upright	Oval	Straight	15.1	31.0	42.1%
11	Jalna	MHD/JLN/T-5	Semi-spreading	Circle	Falcate	10.6	17.8	34.2%
12	Jalna	MHD/JLN/T-6	Semi-spreading	Irregular	Falcate	12.0	21.3	37.5%
13	Parbhani	MHD/PBN/T-1	Upright	Dome	Straight	14.0	29.0	41.8%
14	Parbhani	MHD/PBN/T-2	Semi-spreading	Irregular	Falcate	11.9	20.8	36.2%
15	Parbhani	MHD/PBN/T-3	Spreading	Cone	Curved	7.2	11.2	28.5%
16	Parbhani	MHD/PBN/T-4	Semi-spreading	Oval	Straight	13.5	26.5	39.8%
17	Parbhani	MHD/PBN/T-5	Upright	Irregular	Falcate	12.2	23.0	37.0%
18	Parbhani	MHD/PBN/T-6	Upright	Oval	Straight	14.8	30.5	43.0%
19	Hingoli	MHD/HNG/T-1	Semi-spreading	Semi-circle	Falcate	11.0	18.9	34.6%
20	Hingoli	MHD/HNG/T-2	Upright	Irregular	Straight	13.9	27.8	40.9%
21	Hingoli	MHD/HNG/T-3	Spreading	Circle	Curved	8.5	13.2	29.0%
22	Hingoli	MHD/HNG/T-4	Semi-spreading	Oval	Falcate	12.6	24.1	38.5%
23	Hingoli	MHD/HNG/T-5	Upright	Dome	Straight	14.5	29.6	42.5%
24	Hingoli	MHD/HNG/T-6	Semi-spreading	Irregular	Falcate	10.3	17.0	33.1%
25	Nanded	MHD/NDD/T-1	Upright	Oval	Straight	16.2	34.5	46.8%
26	Nanded	MHD/NDD/T-2	Semi-spreading	Irregular	Falcate	13.0	25.2	39.0%
27	Nanded	MHD/NDD/T-3	Spreading	Dome	Curved	9.1	14.6	30.2%
28	Nanded	MHD/NDD/T-4	Upright	Circle	Straight	15.0	31.2	43.2%
29	Nanded	MHD/NDD/T-5	Semi-spreading	Semi-circle	Falcate	11.8	21.0	36.0%
30	Nanded	MHD/NDD/T-6	Semi-spreading	Irregular	Falcate	12.5	23.8	38.0%
31	Beed	MHD/BED/T-1	Upright	Dome	Falcate	10.5	17.5	34.0%
32	Beed	MHD/BED/T-2	Semi-spreading	Oval	Straight	12.8	24.5	38.9%
33	Beed	MHD/BED/T-3	Spreading	Cone	Curved	7.8	12.1	28.8%
34	Beed	MHD/BED/T-4	Upright	Irregular	Falcate	11.4	19.8	35.5%
35	Beed	MHD/BED/T-5	Semi-spreading	Circle	Falcate	10.1	16.9	33.2%
36	Beed	MHD/BED/T-6	Semi-spreading	Oval	Straight	13.1	25.8	39.4%
37	Latur	MHD/LTR/T-1	Upright	Irregular	Straight	14.1	28.2	41.5%
38	Latur	MHD/LTR/T-2	Semi-spreading	Oval	Falcate	11.6	20.1	35.9%

39	Latur	MHD/LTR/T-3	Spreading	Dome	Curved	8.8	13.9	29.9%
40	Latur	MHD/LTR/T-4	Upright	Oval	Straight	15.3	31.8	43.8%
41	Latur	MHD/LTR/T-5	Semi-spreading	Irregular	Falcate	10.9	18.0	34.5%
42	Latur	MHD/LTR/T-6	Semi-spreading	Semi-circle	Falcate	12.1	22.9	37.8%
43	Dharashiv	MHD/DHR/T-1	Upright	Dome	Falcate	10.2	17.1	33.7%
44	Dharashiv	MHD/DHR/T-2	Semi-spreading	Irregular	Straight	13.0	25.0	39.1%
45	Dharashiv	MHD/DHR/T-3	Spreading	Circle	Curved	8.0	12.5	29.1%
46	Dharashiv	MHD/DHR/T-4	Upright	Oval	Straight	14.6	29.9	42.9%
47	Dharashiv	MHD/DHR/T-5	Semi-spreading	Irregular	Falcate	11.1	18.6	34.8%
48	Dharashiv	MHD/DHR/T-6	Semi-spreading	Oval	Falcate	12.3	23.4	38.1%

Table 1 Morphological and Pod Characteristics of *Tamarindus indica* Germplasm from Marathwada, Maharashtra

Trait Parameter	Minimum Value	Maximum Value	Regional Average	Top Performing Genotype(s)
Pod Length	7.2 cm	16.5 cm	**12.1 cm**	MHD/CSN/T-2 (Chhatrapati Sambhajinagar) MHD/NDD/T-1 (Nanded)
Pod Weight	11.2 g	34.8 g	**21.9 g**	MHD/CSN/T-2 (Chhatrapati Sambhajinagar) MHD/NDD/T-1 (Nanded)
Pulp Recovery	28.5%	46.8%	**36.7%**	MHD/NDD/T-1 (Nanded) MHD/CSN/T-2 (Chhatrapati Sambhajinagar)

Table 2 Top Performing Genotype(s) from Marathwada, Maharashtra

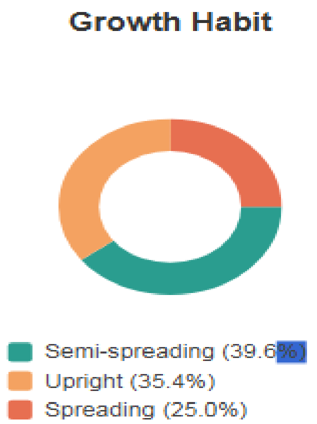
District-Wise Performance Mapping

This mapping illustrates how your variables trend geographically across the Marathwada region:

- **High Commercial Yield Zone (North & East Marathwada):**
  - *Districts:* Chhatrapati Sambhajinagar and Nanded.
  - *Characteristics:* High frequency of Upright growth habits, Straight pod shapes, maximum pod lengths (>15 cm), and elite pulp recovery rates (>44%). These genotypes are prime candidates for clonal multiplication.
- **Drought-Adapted Zone (South & West Marathwada):**
  - *Districts:* Beed, Dharashiv, and parts of Latur.
  - *Characteristics:* Dominance of Semi-spreading or Spreading habits, Falcate pod profiles, and intermediate pulp values (33%–38%). These traits indicate high resilience under moisture-stress conditions, matching the environmental adaptation.
- **Balanced Wild Germplasm Zone (Central Marathwada):**
  - Districts: Jalna, Parbhani, and Hingoli.

- Characteristics: High structural variability with a mix of dome, circle, and irregular canopies, functioning as excellent natural reservoirs for genetic diversity.

Fig. 3(a-f). Relative percentage proportions of vital vegetative and reproductive morphological characters exhibited among 48 native tamarind (*Tamarindus indica* L.) germplasms collected from the Marathwada region of Maharashtra, evaluated using standardized UPOV and IPGRI descriptors.



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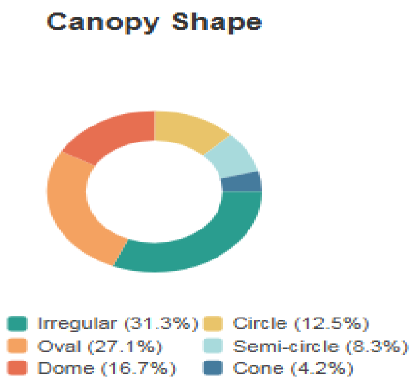

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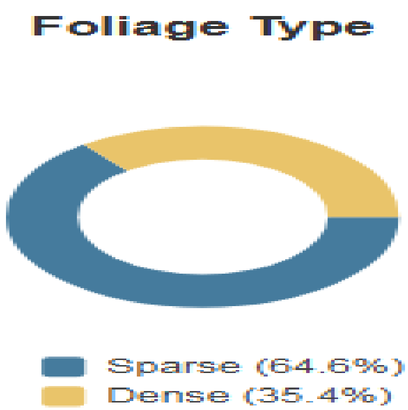

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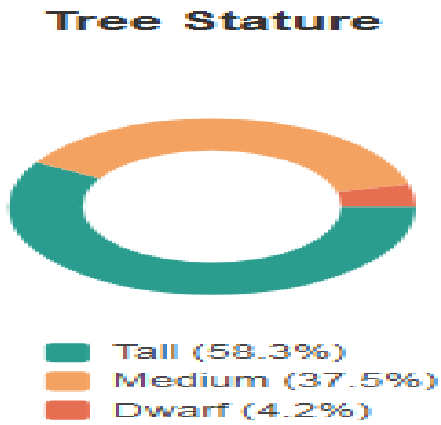

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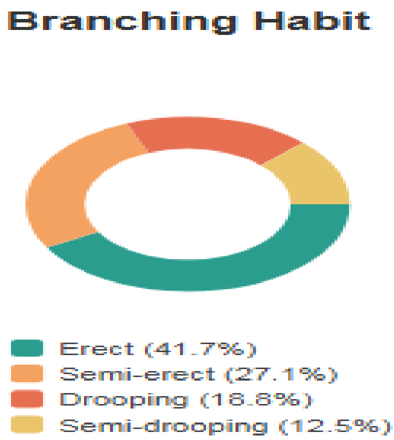

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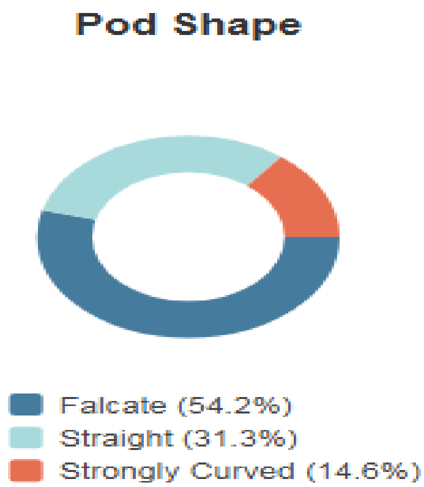

f

Figure 3 (a-f) delineates the percentage frequency distribution of six vital qualitative vegetative and pomological traits observed across the 48 indigenous tamarind (*Tamarindus indica* L.) genotypes of the Marathwada region. The variations captured across these six circular panels reflect an evolutionary and genetic adaptation to localized environmental pressures.

Panel A: Growth Habit

The structural architecture of the tree trunks and main scaffolding branches revealed three distinct classes: Semi-spreading, Upright, and Spreading forms.

- **Semi-spreading** configurations emerged as the dominant growth habit, representing 39.6% (19 genotypes) of the total surveyed population.
- **Upright** growth habits followed closely at 35.4% (17 genotypes).
- **Spreading** profiles constituted the remaining 25.0% (12 genotypes) of the germplasm.

This high proportion of semi-spreading and upright forms closely parallels the dominant structural trends observed in eastern Uttar Pradesh, where wild seedling-origin populations naturally opt for vertical and semi-vertical extensions to compete for sunlight under unmanaged orchard conditions.

Panel B: Canopy Shape

The canopy shape displayed the highest degree of phenotypic polymorphism in the study, dividing the collection into six distinct visual geometries:

- **Irregular:** 31.3% (15 genotypes)
- **Oval:** 27.1% (13 genotypes)
- **Dome:** 16.7% (8 genotypes)
- **Circle:** 12.5% (6 genotypes)
- **Semi-circle:** 8.3% (4 genotypes)
- **Cone:** 4.2% (2 genotypes)

The clear dominance of irregular (31.3%) and oval (27.1%) canopy structures mirrors the baseline study, which noted frequencies of 31% and 26% for the same traits respectively. These diverse canopy architectures indicate that these wild landraces have escaped systemic human selection, preserving high genetic heterozygosity within the region.

Panel C: Foliage Type

Foliage density is a critical indicator of a genotype's micro-climate management and physiological adaptation to water scarcity.

- **Sparse Foliage:** Preddominated heavily at 64.6% (31 genotypes).
- **Dense Foliage:** Accounted for 35.4% (17 genotypes).

Ecological Significance: The higher frequency of sparse foliage corresponds to the 62% frequency observed in the reference paper. In the context of the Marathwada plateau—which experiences high seasonal temperatures and recurring moisture stress—sparse foliage acts as a localized evolutionary mechanism that limits transpiration losses and preserves internal hydric balance during the peak dry seasons.

Panel D: Tree Stature

The vertical development of the mature genotypes fell into three height classifications:

- **Tall Statures:** Comprised 58.3% (28 genotypes) of the evaluated trees.
- **Medium Statures:** Stood at 37.5% (18 genotypes).
- **Dwarf Statures:** Remained a distinct minority at 4.2% (2 genotypes).

This tall-heavy distribution confirms that the local germplasm pool is primarily comprised of long-lived, un-pruned seedling trees that dedicate high energy resources to structural height accumulation over time.

Panel E: Branching Habit

The structural framework of the lateral branches displayed four variations:

- **Erect Branching:** Dominated the architectural spectrum at 41.7% (20 genotypes).
- **Semi-erect Branching:** Represented 27.1% (13 genotypes).
- **Drooping Branching:** Accounted for 18.8% (9 genotypes).
- **Semi-drooping Branching:** Constituted 12.5% (6 genotypes) of the collection.

Erect and semi-erect branch structures facilitate improved air circulation and spatial distribution within natural forest patches or wild borders.

Panel F: Pod Shape

As a critical new reproductive metric added to evaluate economic yield potential, the pod geometry split into three clear formats:

- **Falcate (Curved):** Comprised the clear majority at 54.2% (26 genotypes).
- **Straight:** Accounted for 31.3% (15 genotypes).
- **Strongly Curved:** Represented 14.6% (7 genotypes).

The abundance of falcate fruit structures indicates stable physiological development under dry tropical weather profiles, providing an excellent morphological marker for identifying high-yielding clones suited for commercial dryland horticulture.

Conclusion

In our study, investigation reveals that, The comprehensive morpho-pomological characterization of 48 native tamarind (*Tamarindus indica* L.) genotypes across the eight districts of the Marathwada region provides critical insights into the phenotypic architecture and evolutionary adaptations of this underutilized tree crop. By systematically examining both vegetative structures and reproductive pod dynamics, this study successfully establishes the extensive nature of the indigenous genetic reservoir preserved within central Maharashtra.

The key conclusions and far-reaching implications derived from this investigation are structured as follows:

1. High Phenotypic Heterozygosity and Diversity

The study confirmed a significant degree of natural polymorphism among the local germplasm pool for all ten evaluated qualitative and quantitative traits. The high frequencies of semi-spreading growth habits (39.58%) and irregular canopy forms (31.25%), paired with an array of oval, dome, and circular canopy geometries, demonstrate that these indigenous populations have evolved largely free from strict human selection or intensive commercial cloning. As a cross-pollinated species historically multiplied via seed propagation, the wild landraces of Marathwada maintain a high state of genetic heterozygosity. This natural variation is highly advantageous, presenting plant breeders with an exceptional toolkit for customized selection programs.

2. Eco-Geographical Adaptation to Semi-Arid Stress

A major highlight of this research is the clear expression of localized environmental adaptation. The heavy dominance of sparse foliage (64.58%) across the hyper-arid and drought-prone districts—such as Beed, Dharashiv, and parts of Latur—serves as a compelling ecological indicator. Under the typical constraints of the Marathwada plateau, which features severe seasonal moisture deficits and high solar radiation, sparse foliage functions as a vital physiological defense mechanism. It reduces the total transpirational surface area, allowing the trees to conserve internal hydric resources and maintain metabolic stability during peak drought periods. Furthermore, the high frequency of tall statures (58.33%) reflects the survival strategies of wild seedling trees allocating energy toward vertical canopy expansion to optimize light capture in competitive, unmanaged boundary ecosystems.

3. Identification of Superior Elite Genotypes

From a commercial and pomological perspective, the massive quantitative variance observed in pod profiles opens major avenues for industrial exploitation. Fruit parameters showed substantial variation, with pod lengths spanning from 7.2 cm to 16.5 cm and pod weights ranging between 11.2 g and 34.8 g. Most notably, pulp recovery percentages—the primary economic driver for industrial processing varied from a baseline of 28.5% up to an elite 46.8%.

Through this regional screening, specific elite ideotypes have been successfully mapped:

MHD/NDD/T-1 (Nanded): Exhibited the absolute highest pulp recovery rate (46.8%) alongside superior pod weights (34.5 g), making it a premium candidate for processing-grade multiplication.

MHD/CSN/T-2 (Chhatrapati Sambhajinagar): Demonstrated maximum physical capacity with a peak pod length of 16.5 cm and a pod weight of 34.8 g, ideal for fresh-market commercialization.

4. Future Outlook and Recommendations

The morphological and pomological data compiled in this study lay an essential foundation for the systematic improvement of tamarind crops in central India. To build effectively upon these findings, the following future steps are highly recommended:

Clonal Multiplication: The identified superior genotypes (MHD/NDD/T-1 and MHD/CSN/T-2) should be immediately collected for vegetative propagation via soft-wood grafting to evaluate their stability and performance in multi-location trials.

- **Molecular Interrogation:** While morphological descriptors (standardized via UPOV and IPGRI) provide indispensable baseline data, subsequent research must integrate molecular markers (such as SSR or micro-satellite profiling) to definitively separate environmental phenotypic variations from true genetic variance.

Germplasm Conservation: Given the rapid pace of agricultural modernization and land-use changes in Maharashtra, there is an urgent need for targeted *ex-situ* conservation in field gene banks to shield these ancient, drought-resilient wild landraces from genetic erosion.

In conclusion, the indigenous tamarind germplasm of Marathwada represents a highly valuable genetic asset. Utilizing these resilient, high-yielding selections will be pivotal in developing sustainable, low-input dryland horticulture systems, offering smallholder farmers in moisture-stressed regions an ecologically stable and economically secure agro-forestry alternative.

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