RESEARCH ARTICLE

How Do Habitat and Seasonality Shape the Adaptive Strategies of *Madhuca indica* Gmel?

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Abstract

This study aims to investigate the morphological, physiological, and ecological responses of *Madhuca indica* Gmel. to contrasting environmental conditions in wild and cultivated habitats across two distinct seasons (monsoon and summer). To assess the impact of habitat and seasonality, we compared four cultivated and four wild individuals based on foliar biomass, leaf relative water content, leaf area, trichome density, stomatal density, soil pH, electrical conductivity (EC), and other morphological parameters. While we anticipated significant differences between wild and cultivated plants, our findings revealed a more nuanced response. A comparative analysis of the two habitats and seasons highlighted significant positive and negative correlations ($p < 0.05$) between various parameters. By establishing threshold values for each parameter, we categorized plants as susceptible, moderately tolerant, and highly tolerant. The observed plasticity in plant responses indicates their ability to adapt to specific moisture regimes. ANOVA revealed significant differences in trichome density ($p = 0.01$), soil pH (0.02), EC, and TDS ($p = 0.00$) in wild habitat and two distinct seasons. These results provide valuable insights into the adaptive strategies of *M. indica*.

Keywords: *Madhuca indica*, Physiological traits, Habitat variation, seasonality, -- Correlation, Single-way ANOVA, Adaptive strategies.

Highlights

- Significant habitat-season interactions ($p < 0.05$) were observed.
- A key finding is the significant seasonal influence on foliar trichome density ($p = 0.01$), soil pH ($p = 0.02$), EC, and TDS ($p = 0.00$), particularly in wild populations of *Madhuca indica* Gmel.

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Introduction

Madhuca indica Gmel., the mahua plant is a deciduous, medium-sized tree of the Sapotaceae family. Typically reaching heights of 12 to 18 meters and girths of 2-4 meters, it thrives in dry tropical and subtropical climates with temperatures ranging from 1.7 to 48.5°C and annual rainfall between 750 and 2000 mm. This species is known for its adaptability and can be found throughout India, spanning the region from the Indo-Gangetic plains down to Tamil Nadu. *M. indica* is a valuable resource with multiple uses. It is valued for its ecological resilience, cultural importance, and economic potential, including applications in medicine, biodiesel production, and agroforestry. (Wani and Ahmad, 2013; *Sarkar et al., 2017*). It is one of the hardy trees of the dry region (Singh and Singh, 2020). Phenotypic plasticity is a biological characteristic that has been widely recognized as an important feature of an organism's development, function and evolution in its environment (Sultan, 2000). Previous studies have reported genetic variability in *M. indica* with respect to flowering, yield, fruit quality, and stress tolerance, highlighting its importance for breeding and conservation programs (Singh *et al.*, 2005; Bhargava *et al.*, 2017). However, despite such progress, comprehensive evaluations of adaptive plasticity that integrate morphological, physiological, and ecological traits across habitats and seasons remain limited.

Addressing research gap, foliar morpho-physiological characters [fresh weight (FW); turgid weight (TW); dry weight (DW); relative water content (RWC); leaf area (LA), stomatal density (SD); trichome density (TD); number of leaves (NOL)], stem circumference (SC), and soil parameters (pH, electric conductivity (EC), and total dissolved solutes (TDS)) were selected for seasonal and habitat-based responses. By analyzing these traits across cultivated and wild populations during summer and monsoon seasons, the study aims to assess the adaptive responses of *M. indica* at a regional scale.

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Methodology

Morphological, Physico-chemical parameters and Soil Collection

Godhra city of Gujarat is located at 22.776° N 73.618° E. Plant and soil samples were collected during the summer (March-May) and monsoon (June-October) seasons of 2023 from Godhra tehsil of Panchmahal district of Gujarat. Cultivated plant samples were collected from Godhra city, while wild plant samples were collected from the forest area of Samli village of Godhra Tehsil. A total of eight sampling units were selected for the study and tagged with serial numbers 1 to 8. Among those 1 to 4 plants are cultivated plants and 5 to 8 plants are wild plants. Five fully expanded leaves were collected from sun-exposed branches to minimize the variation due to leaf age and micro-environment. The stem circumference (SC) at breast height was measured for all plants. The number of leaves was counted on the fully expanded branch with maximum sun exposure at the time of collection. Soil pH, electrical conductivity (EC), and total dissolved solids (TDS) were measured in 1:5 soil-water solutions from 0 to 30 cm soil samples around each plant, using a digital CPEX meter.

Microscopical parameters

To assess stomatal characteristics, leaf imprints were obtained from the basal, middle, and apical regions of standardize leaves described above. Impressions of the upper and lower epidermis were made using transparent nail polish, peeled, and mounted on glass slides. Stomatal frequency was determined using the method described by Waghmode and Joshi (1979). Stomatal and trichome densities were quantified per square millimeter (mm^2) from the lower leaf surface. Mean values from basal, middle, and apical regions were considered for further analysis (Dipa and Daniel, 2011).

Physiological parameters

Estimation of relative water content (RWC) was done using standardized leaves, which were collected and sealed in polythene bags to prevent water loss during transportation to the lab. Leaf area was measured using the traditional graph paper method (Pandey and Singh, 2011). FW of leaves was recorded immediately. Distilled water was used to soak leaves, kept for 4 hours to attain maximum turgidity. TW was recorded after gently blotting the leaves to remove surface water. Finally, leaves were oven-dried at 60°C for 72 hours to obtain dry weight (DW) (Sade *et al*., 2014). RWC was calculated using the following formula:

$$\text{RWC (\%)} = (Fresh\ weight - Dry\ weight)/\ (Turgid\ \text{weight} - Dry\ weight\ ) * 100.$$ (Barrs, 1968; Lugojan and Ciulca, 2011)

Data Analysis

The quantitative data encompassing foliar traits (biomass, stomatal and trichome density, area, RWC) and soil parameters (pH, EC, TDS) were organized and managed in Microsoft Excel 2016 MSO (16.0.4266.1001). Subsequent statistical analysis was performed using PAST 4.03 software. Statistical analysis, including mean, standard deviation, and standard error, was calculated for each parameter. Correlation analysis (*p-value* ≤ 0.05) was employed to assess the relationships between variables by Pearson's correlation coefficient test. Further significance of variation during summer and monsoon was analysed by Single Factor ANOVA (*p-value* ≤ 0.05). To categorize plant species based on their tolerance to specific environmental factors, threshold values were determined for each parameter. Plants were categorized as tolerant, moderately tolerant, or susceptible plants based on their values relative to the mean ± standard deviation. This categorization approach allowed for the identification of plant species with varying levels of tolerance to the assessed environmental factors.

Results

The differential responses of cultivated and wild plants to seasonal variations are highlighted in Figs 1 and 2, respectively. Cultivated plants, benefiting from human intervention, exhibit higher growth and physiological activity, particularly during the summer. However, wild plants, despite facing harsher conditions, demonstrate remarkable resilience and water use efficiency. These findings underscore the importance of understanding the physiological mechanisms underlying plant responses to environmental stress and the potential for developing more sustainable cultivation practices of *Madhuca indica.*

The provided data (Table 1) presents a comparison of various physiological, morphological, and ecological parameters of cultivated and wild plants of *Madhuca indica* during the summer and monsoon seasons.

Seasonal comparison: Summer

Both cultivated and wild plants exhibit higher values for most parameters during the summer, indicating increased growth and physiological activity.

Monsoon

While some parameters decrease during the monsoon, others, such as leaf area and water content, increase. This suggests that the plants are adapted to utilize the increased water availability during this season.

Cultivation difference

Cultivated Plants Generally show higher values for most parameters, especially during the summer. This could be attributed to better soil conditions, irrigation, and fertilizer inputs (Fig. 1).

Wild Plants

While they may not exhibit as high values as cultivated plants, they demonstrate remarkable resilience, particularly during the monsoon (Fig. 2). These findings suggest that wild plants display a higher degree of adaptation to natural environmental fluctuations.

Lower stomatal density

In cultivated plants during the summer suggests that they may have lower water use efficiency compared to wild plants. This could be due to their reliance on irrigation and fertilizers. Wild plants, with their higher stomatal density, may be better adapted to conserve water, especially during the dry summer months.

Correlation analysis in cultivated plants (*p-value* ≤ 0.05):

Correlation coefficients, presented in Figures 3a and 3b for summer and monsoon seasons, quantify the linear association between parameters. These values, ranging from -1 to +1, represent perfect inverse, no, and perfect direct correlations, respectively.

Correlation analysis in cultivated plants

FW, TW and DW has a strong positive correlation in both seasons. TDS and EC are linked positively in summer (R=0.99) and monsoon (R=1.00). For the Summer season, RWC has a strong positive correlation with DW (R=0.95). DW, RWC are strongly

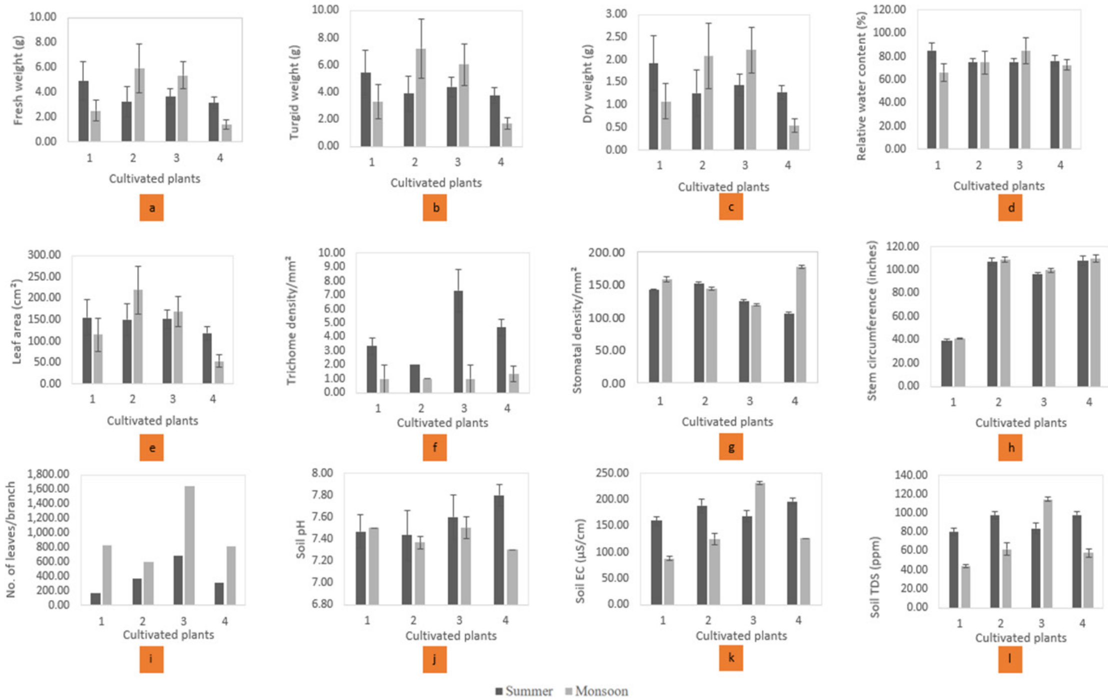

Fig. 1: Different graphs specify the responses of Morpho-physiological parameters: **1a**- Fresh weight (FW), **1b**-Turgid weight(TW), **1c**-Oven dry weight(DW),**1d**- leaf relative water content (RWC) and **1e-**Leaf area (LA), **1f**- trichome density(TD), **1g**- stomatal density (SD), **1h**- stem circumference (SC), **1i**- number of leaves(NOL) and physico-chemical tests of **1j**- soil pH, **1k**-electric conductivity(EC), and **1l**-Total dissolved solutes(TDS) of the cultivated plants of *Madhuca indica* from Godhra during Summer and Monsoon season. Cultivated plants are tagged with no.1,2,3 and 4.

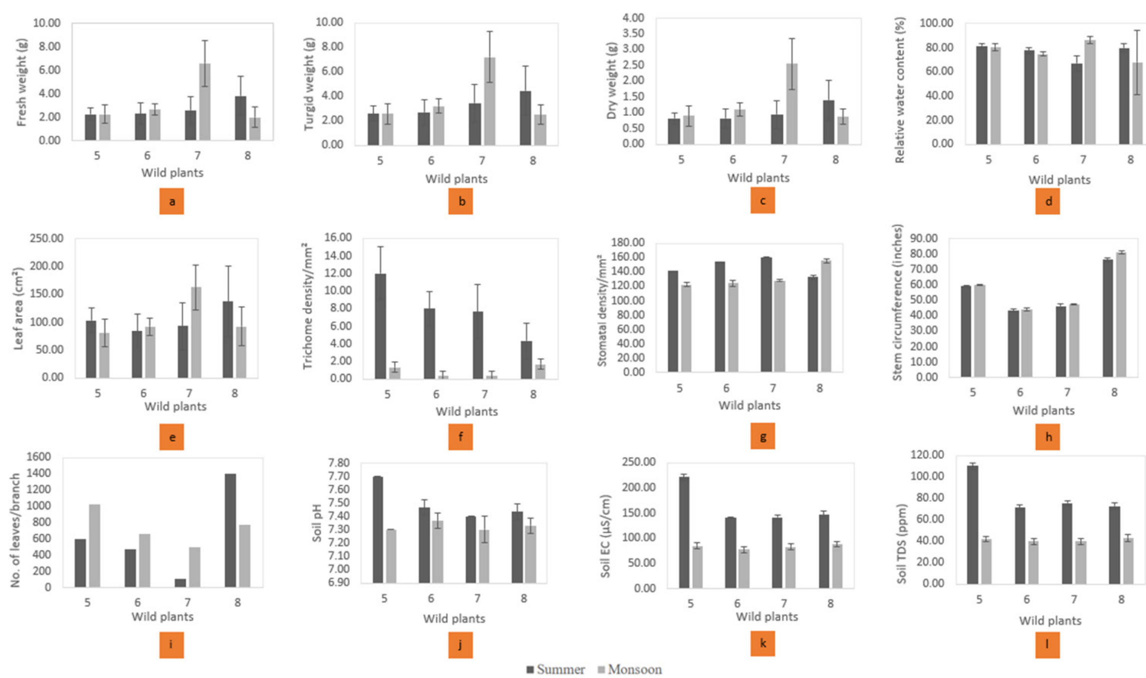

Fig. 2: Different graphs specify the responses of Morpho-physiological parameters: 2**a**- Fresh weight (FW), **2b**-Turgid weight(TW), **2c**-Oven dry weight(DW), **2d**- leaf relative water content (RWC) and **2e-**Leaf area (LA), **2f**- trichome density(TD), **2g**- stomatal density (SD), **2h**- stem circumference (SC), **2i**- number of leaves(NOL) and physico-chemical tests of **2j**- soil pH, **2k**-electric conductivity(EC), and **2l**-Total dissolved solutes(TDS) of the wild plants of *Madhuca indica* from Godhra during Summer and Monsoon season. Plants are tagged with no.5,6,7 and 8

Table 1: Descriptive statistical analysis of morphological, physiological, and ecological parameters of cultivated and wild plants during summer and monsoon season

		Summer			*Monsoon*		
		Min ± SD	*Max ± SD*	*Mean ± SD*	*Min ± SD*	*Max ± SD*	*Mean ± SD*
Cultivated Plants	FW	3.15 ± 0.44	4.91 ± 1.54	3.74 ± 0.81	1.38 ± 0.38	5.92 ± 1.94	3.80 ± 2.20
	TW	3.74 ± 1.68	5.42 ± 1.66	4.36 ± 0.76	1.68 ± 0.40	7.22 ± 2.20	4.56 ± 2.52
	DW	1.26 ± 0.51	2.08 ± 0.72	1.48 ± 0.31	0.54 ± 0.14	2.22 ± 0.51	1.48 ± 0.81
	RWC	75.09 ± 3.30	85.08 ± 6.44	77.96 ± 4.78	66.38 ± 7.46	85.02 ± 11.18	74.74 ± 7.72
	LA	118.45 ± 15.11	155.34 ± 40.99	143.79 ± 17.05	53.16 ± 14.29	219.68 ± 56.14	139.19 ± 71.59
	PH	7.43 ± 0.23	7.80 ± 0.10	7.58 ± 0.17	7.30 ± 0.00	7.50 ± 0.00	7.42 ± 0.10
	EC	159.33 ± 7.57	196.67 ± 6.43	178.17 ± 17.42	88.00 ± 3.46	230.67 ± 3.06	142.50 ± 61.40
	TDS	80.00 ± 3.61	98.33 ± 3.21	90.00 ± 9.38	44.00 ± 1.73	114.67 ± 2.52	69.67 ± 30.98
	SD	91.33 ± 54.86	152.00 ± 2.65	131.42 ± 20.01	119.00 ± 1.73	177.00 ± 2.00	149.67 ± 24.50
	TD	2.00 ± 0.00	7.33 ± 1.53	4.33 ± 2.28	1.00 ± 0.00	1.33 ± 0.58	1.08 ± 0.17
	SC	39.37 ± 1.01	107.87 ± 4.01	87.71 ± 32.63	41.21 ± 0.82	109.57 ± 3.01	89.83 ± 32.73
	NOL	174.00	694.00	386.25 ± 220.40	600.00	1648.00	974.00 ± 461.62
Wild Plants	FW	2.25 ± 0.53	3.80 ± 1.66	2.73 ± 0.73	2.00 ± 0.87	6.59 ± 1.97	3.38 ± 3.87
	TW	2.58 ± 0.63	4.44 ± 2.01	3.28 ± 0.86	2.49 ± 0.59	7.21 ± 2.09	3.87 ± 2.25
	DW	0.81 ± 0.19	1.40 ± 0.64	0.99 ± 0.28	0.87 ± 0.21	2.55 ± 0.81	1.36 ± 0.80
	RWC	67.05 ± 6.19	81.44 ± 2.00	76.56 ± 6.52	67.92 ± 1.85	86.26 ± 26.23	77.43 ± 7.83
	LA	84.12 ± 30.29	137.52 ± 63.14	104.60 ± 23.32	80.52 ± 15.13	162.62 ± 41.07	106.98 ± 37.51
	PH	7.40 ± 0.00	7.70 ± 0.00	7.50 ± 0.14	7.30 ± 0.00	7.37 ± 0.10	7.33 ± 0.3
	EC	141.33 ± 1.15	221.33 ± 5.77	162.67 ± 39.19	77.33 ± 5.29	88.00 ± 6.11	83.50 ± 4.53
	TDS	71.67 ± 2.08	110.67 ± 2.89	82.75 ± 18.69	40.00 ± 2.52	43.33 ± 3.51	41.42 ± 1.69
	SD	132.67 ± 3.06	160.67 ± 0.58	147.25 ± 12.51	122.33 ± 1.53	155.67 ± 4.04	132.67 ± 15.53
	TD	4.33 ± 2.08	12.00 ± 3.00	8.00 ± 3.14	0.33+0.58	1.67 ± 0.58	0.92 ± 0.69
	SC	43.33 ± 1.04	76.33 ± 1.26	56.33 ± 15.01	44.00 ± 0.40	81.23 ± 1.00	58.27 ± 16.81
	NOL	109.00	1404.00	643.50 ± 546.93	496.00	1030.00	737.50 ± 224.69

Here, FW, TW, DW are Fresh weight, Turgid Weight and Dry weight respectively, and are expressed in g. RWC, LA, pH,
EC, TDS and DOS are Relative Water Content in %, Leaf Area in cm^2, Potential of Hydrogen ion, Electrical Conductivity in µS/cm, Total Dissolved Salt in ppm, Number of Leaves and Diameter of Stem, respectively. Stomatal Density (SD) and Trichome Density (TD) are expressed as mm^2.

related, suggesting that deeper soil holds more water; Stomatal density (SD) has a strong inverse correlation with pH (R= -0.99); SC has a strong negative correlation with FW (R= -0.99), TW (R= -0.98), and DW (R= -0.99) and RWC (R= -0.98). For the Monsoon season, LA has a strong positive correlation with FW (R= 0.97) and TW (R=0.99); Leaf area (LA) is positively correlated with water content, suggesting that plants with larger leaves might have better water uptake; RWC has a linear positive correlation with EC (R= 0.98) and TDS (R= 0.97).

Correlation analysis in wild plants

FW, TW and DW have a strong positive correlation in both seasons (Fig. 3 a & 3 b). In Summer, pH exhibits a strong positive correlation with EC (R= 0.97) and TDS (R=0.96); EC and TDS have a strong positive relation (R=0.99); Stem circumference is linked with leaf area (R=0.98); NOL and EC are not related in summer (R=0.00). During the monsoon season, TD and TDS are in linear correlation (R=1.00); SC and TDS are closely related (R=0.95).

Single Factor ANOVA

A combination of statistical analysis with biological knowledge gives valuable insights into the factors influencing plant growth and development in different environments. The provided single-way ANOVA (Table 2) is a statistical tool used to compare means of various parameters (FW, TW, DW, etc.) between cultivated and wild plants. The table presents the results of a Single-way ANOVA, comparing the effects of plant type (cultivated vs. wild) and season (summer vs. monsoon) on various plant parameters (FW, TW, DW, etc.).

Results of pH (0.02), EC (0.00), TDS (0.00), and TD (0.01) are considered statistically significant between the summer and monsoon seasons. These are the significant differences

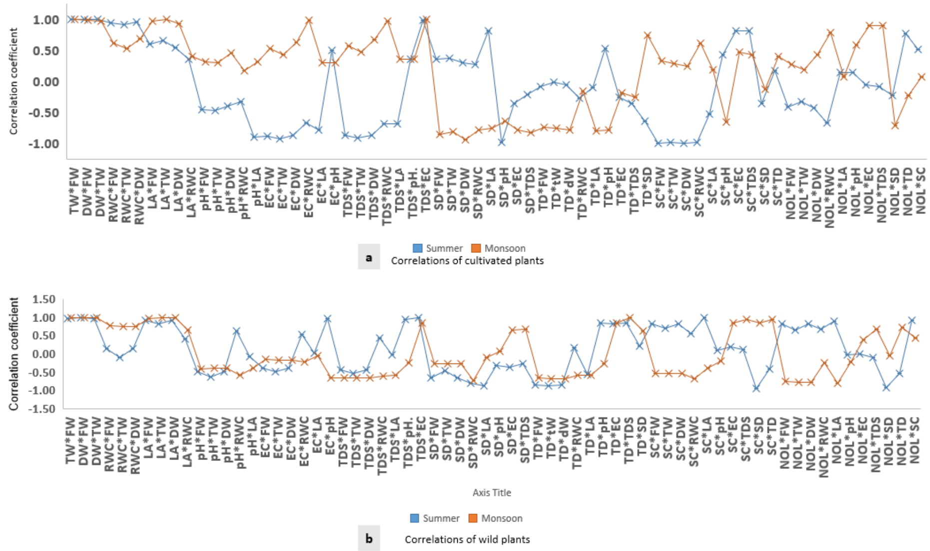

Fig. 3: Correlation (at *p-value* less than or equal to 0.05) among morphological, physiological and ecological traits of **a** cultivated and **b**- wild *Madhuca indica* Gmel. during the Summer and Monsoon season from Godhra

between cultivated and wild plants for these parameters. So here, null hypothesis can be rejected. The significant differences in pH, EC and TDS suggest that cultivated and wild plants may occupy different ecological niches or experience different soil conditions. The significant difference in TD indicates that cultivated and wild plants might be exposed to different temperature regimes and may effect on trichome distribution on leaf surface.

The P-values for FW, TW, DW, RWC, LA, SC, and NOL are greater than 0.05, suggesting no significant differences between cultivated and wild plants for these parameters. So, the null hypothesis cannot be rejected. The lack of significant differences in FW, TW, DW, and RWC suggests that both cultivated and wild plants may have similar strategies for water uptake and biomass accumulation. The non-significant difference in LA indicates that both types of plants may have similar leaf area characteristics.

The Tables (3, 4, 5, 6) suggest that, regardless of the season, the majority of plant traits tend to exhibit moderate tolerance to the environmental conditions. This indicates a general adaptability of the plants to the prevailing conditions. However, there are variations in the number of highly tolerant and susceptible traits across different sampling units and seasons.

Here, HTV is the high threshold value, LTV is the low threshold value, SP is the total number of susceptible plants, MTP is the total number of moderately tolerant plants, HTP is the total number of highly tolerant plants, PWHT is the sampling plant that is highly tolerant, and PWS is the sampling plant that is susceptible. Sign '-' indicates not any plant is highly tolerant or susceptible for that trait (i.e., moderately tolerant).

Here, HTV is the high threshold value, LTV is the low threshold value, SP is the total number of susceptible plants, MTP is the total number of moderately tolerant plants, HTP is the total number of highly tolerant plants, PWHT is the sampling plant which is highly tolerant, and PWS is the sampling plant which is susceptible. Sign '-' indicates no plant is highly tolerant or susceptible for that trait (i.e. moderately tolerant).

Percentage analysis for each trait

Foliar biomass exhibited both increases and decreases (Fig. 4 a) during the monsoon season for both cultivated and wild *Madhuca indica* plants. Cultivated plants 2 and 3 experienced increases, while plants 1 and 4 showed decreases. Among wild plants, numbers 5, 6, and 8 increased their biomass, whereas plant 8 decreased.

RWC decreased for six out of eight sampling units. Cultivated plants 1, 2, and 3 experienced RWC reductions ranging from 0.55 to 21.98%, while wild plants decreased by 1.10 to 15.08%. Two cultivated plants 1 and 4 decreased LA by 26.12 and 55.12%, respectively. Wild plants 5 and 7 decreased LA by 22.16 to 32.58%. Conversely, plants 2, 3, 6, and 8 increased LA by 46.56, 11.65, 9.46, and 74.25%, respectively (Fig. 4 b).

The pH of cultivated plant 1 increased by 0.45%. However, for all other cultivated and wild plants, soil pH became slightly more acidic during the monsoon compared to the summer (Fig. 4 c). EC and TDS decreased for all sampling units except cultivated plant 3, which showed increases of 37.30% and 36.51%, respectively, during the monsoon.

Three cultivated plants and one wild plant exhibited an increase in stomatal density (Fig. 4 d). Cultivated plant no. 2 experienced a 5.26% decrease, while wild plants 5, 6, and 7 showed decreases ranging from 13.65 to 19.26%. Foliar trichome density decreased for all plants during the monsoon season, ranging from 50.00% to 95.83%.

Stem circumference increased for all plants, ranging from 1.54 to 6.42%. The maximum increment (6.42%) was observed in wild plant 8 (Fig. 4 e). The number of leaves increased for all cultivated and wild plants (Fig. 4 f), ranging from 40.17 to 355.04%, except for wild plant 8, which decreased by 45.29%.

Discussion

This research highlights several morphological, physiological and ecological adaptations of *Madhuca indica* to diverse

Table. 2: One-way ANOVA of seasonal morphological, physiological, and ecological parameters of *Madhuca indica* in cultivated and wild plants

Cultivated plants						wild plants			
Source of Variation		*SS*	*MS*	*F*	*p-value*	*SS*	*MS*	*F*	*p-value*
FW	Between Groups	1.14	1.14	0.37	0.58	1.12	1.12	0.33	0.60
	Within Groups	12.45	3.11			13.53	3.38		
TW	Between Groups	1.42	1.42	0.33	0.60	0.91	0.91	0.25	0.64
	Within Groups	17.23	4.31			14.54	3.63		
DW	Between Groups	0.12	0.12	0.28	0.62	0.32	0.32	0.69	0.45
	Within Groups	1.76	0.44			1.83	0.46		
RWC	Between Groups	5.68	5.68	0.26	0.64	175.49	175.49	0.14	0.72
	Within Groups	86.62	21.65			4917.72	1229.43		
LA	Between Groups	81.76	81.76	0.02	0.89	3.15	3.15	0.05	0.84
	Within Groups	15272.19	3818.05			266.76	66.69		
pH	Between Groups	0.07	0.07	3.36	0.14	0.02	0.02	13.50	0.02*
	Within Groups	0.09	0.02			0.00	0.00		
EC	Between Groups	848.07	848.07	0.44	0.55	5440.07	5440.07	285.76	0.00*
	Within Groups	7787.85	1946.96			76.15	19.04		
TDS	Between Groups	342.52	342.52	0.64	0.47	1568.17	1568.17	399.44	0.00*
	Within Groups	2131.19	532.80			15.70	3.93		
SD	Between Groups	535.12	535.12	0.78	0.43	253.50	253.50	1.00	0.37
	Within Groups	2734.72	683.68			1009.48	252.37		
TD	Between Groups	18.96	18.96	5.31	0.08	52.02	52.02	22.12	0.01*
	Within Groups	14.30	3.57			9.41	2.35		
SC	Between Groups	7.34	7.34	0.21	0.67	7.71	7.71	0.02	0.89
	Within Groups	140.13	35.03			1507.49	376.87		
NOL	Between Groups	477708.17	477708.17	2.74	0.17	620.17	620.17	0.00	0.96
	Within Groups	698052.67	174513.17			931376.67	232844.17		

MS is Mean square value, SS is sum square value, df=4 for within group and df=1 for between group.
* Indicates the study is significant for wild plant parameters: soil pH, EC, TDS and TD (*p-value*<0.05)

environmental conditions that significantly influence plant growth and survival.

Trichomes and Stomatal density

Leaf trichomes played an important role in resistance to pathogens, protecting leaves from excessive temperature and drought stress (Yang *et al*., 2021). In this study, trichome density of cultivated plants in summer is higher (2.00 ± 0.00 to 7.33 ± 1.53 per mm^2) than the monsoon season. Similarly, for wild plants, it is higher (4.33 ± 2.08 to 12.00 ± 3.00 per mm^2) than the monsoon trichome density. Higher trichome density in summer indicates the adaptation of leaves against temperature. In this study, the variations in stomatal densities across different regions suggest that *Madhuca indica* exhibited a degree of plasticity in adapting its stomatal characteristics to local environmental conditions.

RWC

Leaf relative water content (LRWC) is an index of tissue water status and decreases under drought (Zhang *et al*., 2020). Relative water content (RWC) is an important physiological parameter that reflects the balance between water uptake and loss in plants. It plays a significant role in maintaining normal growth and physiological activities. Higher RWC enhances a plant's ability to tolerate environmental stresses such as air pollution and drought by maintaining physiological balance. (Innes and Haron, 2000; Joshi and Swami, 2007; Lugojan and Ciulca, 2011; Tsega and Prasad, 2014; Lohe *et al.,* 2015; Soltys-Kalina *et al*., 2016). In earlier studies, *M. longifolia* exhibited the highest average relative water content of 88.85 ± 0.44 at the least polluted site and 86.258 ± 0.65 at the highly polluted site. This higher water content in *M. longifolia* aids in maintaining its physiological balance under stressful conditions caused by

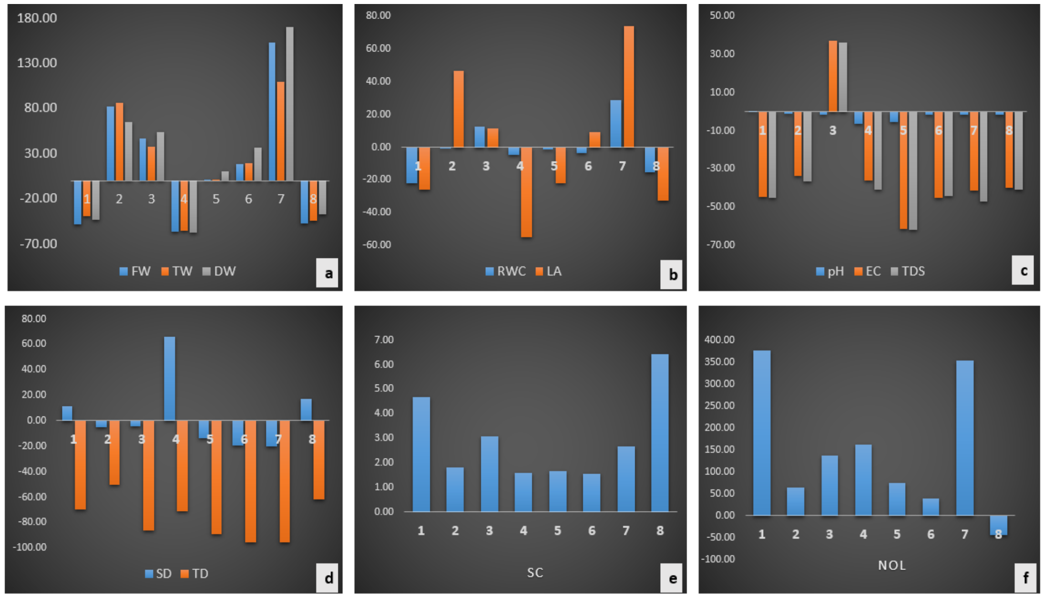

Fig. 4: (a-f) Seasonal Percentage change of morphological, physiological and ecological parameters of plants: X axis represents cultivated plants (1, 2, 3, 4) and wild plants (5, 6, 7, 8) and Y axis represents Percentage difference in monsoon compared to summer

air pollution. However, increased transpiration rates in high pollution environments can lead to reduced relative water content and potential desiccation (Bandara and Dissanayake, 2021). A higher RWC indicated that the plant is well-hydrated, while a lower RWC indicated that the plant was water-stressed. However, achieving 100% RWC is often unrealistic for well-watered plants (Morgan, 1995). In this research, the considerable range in RWC values suggested that *Madhuca indica* could adjust its water content to endure varying degrees of water stress. This study reveals the mean RWC value of Cultivated plants in summer is 77.96 ± 4.78 and in monsoon is 74.74 ± 7.72%. For wild plants in Summer,76.56 ± 6.52% and 77.43 ± 7.83% in the monsoon. There is no significant difference in the water status of leaves in both seasons.

Leaf area

Morphological plasticity, particularly variations in the size and placement of resource-acquiring organs like leaves and roots, is crucial for plant adaptation to varying resource availability (Bazzaz and Harper,1977; Crick and Grime, 1987; Dong *et al.,* 1996). A well-established functional pattern of morphological plasticity involves an increase in leaf area relative to plant biomass under low light conditions. This strategy allows plants to maximize light interception and nutrient acquisition (Smith, 1982; Reich *et al.,* 1998; Poorter, 2001; Navas and Garnier, 2002; King, 2003; Steinger *et al*., 2003). Leaves of drought-tolerant plants develop adaptations such as smaller leaf area, larger leaf thickness, and higher leaf tissue density (Yang *et al*., 2021).

Sites with higher soil moisture, phosphorus, and clay content, as well as lower light intensity, exhibited greater LA in tree species. Conversely, sites with lower soil moisture and higher light intensity had reduced LA. These findings suggest that TDF species, such as *Acacia catechu*, *Dalbergia melanoxylon*, *Eucalyptus officinalis*, and *Lagerstroemia coromandelica*, exhibit morphological plasticity in response to varying environmental conditions (Chaturvedi and Raghuvanshi, 2013).

In our study Cultivated plants has mean leaf area of 143.79 ± 17.05 cm^2 and 139.19 ± 71.59 cm^2, which is larger compared to wild plants 104.60 ± 23.32 cm^2 and 106.98 ± 37.51 cm^2 in summer and monsoon, respectively.

Soil pH, EC and TDS

In the present study, there is a significantly strong positive correlation between pH and EC for cultivated and wild plants for summer season. And strongly positively correlated in monsoon for cultivated plants at R value<0.05. One-way ANOVA results indicate significant variations in soil pH (p = 0.02), EC ($p < 0.001$), and TDS ($p < 0.001$). Earlier Studies on coastal saline soil, EC of 1:5 soil-water extract (EC, in dS m^{-1}) and total soil salt content (St in g kg^{-1}) showed a highly significant linear correlation ($p < 0.01$) (He Y and *et al*.; 2012). Soil pH was acidic in May and June, immediately following spring fertilization. Subsequently, soil pH gradually turned alkaline, reaching its maximum values between December and March. While the differences were subtle, they exhibited definite trends. This pattern aligns with the findings of Murdock, Bates, and Collins (Lockman and Molloy, 1984).

During the pre-monsoon and summer seasons, the soil exhibited a neutral pH (6.87 to 7.23). However, a shift towards a slightly alkaline pH (6.98 to 8.20) was observed post-monsoon. Peak EC values reached 1.72 dS/cm (pre-monsoon), 6.25 dS/cm (post-monsoon), and 1.19 dS/cm (summer). Additionally, a comparison of mean EC values revealed an increase in the post-monsoon period in North Gujarat. This elevated ionic concentration is likely the primary factor contributing to this trend. A very weak correlation existed between soil pH and EC, indicating the concentration of ions present in the soil (Patel *et al*., 2015).

Table 3: Seasonal Threshold Values of Morphological, Physiological, and Ecological parameters in cultivated plants during Summer and Monsoon

Cultivated	*Summer*								*Monsoon*							
Parameter	*Mean*	*HTV*	*LTV*	*SP*	*MTP*	*HTP*	*PWHT*	*PWS*	*Mean*	*HTV*	*LTV*	*SP*	*MTP*	*HTP*	*PWHT*	*PWS*
FW	3.74	4.55	2.93	0	3	1	1	-	3.80	6.00	1.60	1	3	0	-	-
TW	4.36	5.12	3.60	0	3	1	1	-	4.56	7.08	2.03	1	2	1	2	-
DW	1.48	1.78	1.17	0	3	1	1	-	1.48	2.29	0.67	1	3	0	-	4
RWC	77.96	82.73	73.18	0	3	1	1	-	74.74	82.46	67.02	1	2	1	3	1
LA	143.79	160.84	126.75	0	4	0	-	-	139.19	210.77	67.60	1	2	1	2	4
PH	7.58	7.74	7.41	0	3	1	4	-	7.42	7.52	7.32	1	3	0	-	4
EC	178.17	195.59	160.74	1	2	1	4	1	142.50	203.90	81.10	0	3	1	3	-
TDS	90.00	99.38	80.62	1	3	0	-	1	69.67	100.64	38.69	0	3	1	3	-
SD	131.42	151.43	111.41	1	2	1	2	4	149.67	174.17	125.17	0	0	1	4	3
TD	4.33	6.61	2.06	1	3	0	3	2	1.08	1.25	0.92	0	3	1	4	-
SC	87.71	120.34	55.08	1	3	0	-	1	89.83	122.56	57.09	1	3	0	-	1
NOL	386.25	606.65	165.85	0	3	1	3	-	974.00	1435.62	512.38	0	3	1	3	-

Here, HTV is high threshold value, LTV is low threshold value, SP is total number of susceptible plants, MTP is total number of moderately tolerant plant, HTP total number of highly tolerant plant, PWHT is the sampling plant which is highly tolerant, PWS is the sampling plant which is susceptible. Sign '-' indicates not any plant is highly tolerant or susceptible for that trait (i.e. moderately tolerant)

Table 4: Seasonal Threshold Values of Morphological, Physiological, and Ecological parameters in Wild plants during Summer and Monsoon

Wild	Summer								Monsoon							
Parameter	Mean	HTV	LTV	SP	MTP	HTP	PWHT	PWS	Mean	HTV	LTV	SP	MTP	HTP	PWHT	PWS
FW	2.73	3.46	2.00	0	3	1	8	-	3.38	5.54	1.23	0	3	1	7	-
TW	3.28	4.15	2.42	0	3	1	8	-	3.87	6.12	1.62	0	3	1	7	-
DW	0.99	1.27	0.72	0	3	1	8	-	1.36	2.16	0.56	0	3	1	7	-
RWC	76.56	83.08	70.05	1	3	0	0	7	77.43	85.26	69.59	1	2	1	7	8
LA	104.60	127.92	81.28	0	3	1	8	-	106.98	144.50	69.47	0	3	1	7	-
pH	7.50	7.64	7.36	0	3	1	5	-	7.33	7.36	7.29	0	3	1	6	-
EC	162.67	201.86	123.47	0	3	1	5	-	83.50	88.03	78.97	1	3	0	-	6
TDS	82.75	101.44	64.06	0	3	1	5	-	41.42	43.10	39.73	0	3	1	8	-
SD	147.25	159.76	134.74	1	2	1	7	8	132.67	148.20	117.13	0	3	1	8	-
TD	8.00	11.14	4.86	1	2	1	5	8	0.92	1.60	0.23	0	3	1	8	-
SC	56.33	71.34	41.31	0	3	1	8	-	58.27	75.08	41.46	0	3	1	8	-
NOL	643.50	1190.43	96.57	0	3	1	8	-	737.50	962.19	512.81	1	2	1	5	7

Here, HTV is high threshold value, LTV is low threshold value, SP is total number of susceptible plants, MTP is total number of moderately tolerant plant, HTP total number of highly tolerant plant, PWHT is the sampling plant which is highly tolerant, PWS is the sampling plant which is susceptible. Sign '-' indicates not any plant is highly tolerant or susceptible for that trait (i.e. moderately tolerant).

In this study, the soil pH of cultivated plants was 7.58 ± 0.17 in summer and 7.42 ± 0.10 in the monsoon season. For wild plants, it is 7.50 ± 0.14 and 7.33 ± 0.3 in summer and monsoon, respectively, which indicates slightly shift towards acidic pH. Mean EC values of Cultivated plants in summer were 178.17 ± 17.42, and decreased up to 142.50 ± 61.40 µS/cm in the monsoon. For wild plants in summer, 162.67 ± 39.19 and in monsoon, 83.50 ± 4.53 µS/cm. In this study, the soil pH of wild plants in the summer season has a strong positive correlation with EC (R=0.97).

A positive correlation was observed among soil pH and organic matter, potassium, copper, magnesium, and calcium during the summer season. This suggests that increased ionic concentrations (EC) in the soil contribute to higher pH values. Furthermore, the rapid decomposition and nutrient release at elevated temperatures contrast with the slower organic matter accumulation in cooler soil conditions (Brady and Weil, 2004). The electrical conductivity (EC, in dS m^{-1} of a 1:5 soil-water extract) and total dissolved solids (TDS content, St in g kg^{-1}) in coastal saline soils exhibited a highly significant linear

Table 5: Number of traits for adaptive strategy of survival

		Cultivated plants				*Wild plants*			
Season	Sampling unit	1	2	3	4	5	6	7	8
	No. of trait for high tolerance	4	1	2	2	4	0	1	6
Summer	No. of trait for Susceptibility	3	1	0	1	0	0	1	2
	No. of trait for Moderate tolerance	5	10	10	9	8	12	10	4
	No. of trait for high tolerance	0	2	4	2	1	1	5	4
Monsoon	No. of trait for Susceptibility	2	0	1	3	0	1	1	1
	No. of trait for Moderate tolerance	10	10	7	7	11	10	6	7

Here 1 to 4 are cultivated plants, 5 to 8 are wild plants of *M. indica,* Total no. of traits studied for adaptive strategy is 12.

correlation (P < 0.01) in relevant studies. Soil salinity, assessed through EC and TDS, can impact plant growth (He Y *et al.*, 2012). In this study, Strong positive EC-TDS correlations (R=0.99) were observed in cultivated plants (summer) and wild plants (summer, R=0.99 and monsoon, R=1.00).

NOL

Reducing leaf number under water scarcity can be a drought tolerance mechanism or a water conservation strategy in limited soil moisture (Riaz *et al.*, 2013). In this study, the number of leaves increased in the monsoon for all cultivated and wild plants, ranging from 40.17% to 355.04% indicates favourable water requirements, except for wild plant 8, which decreased by 45.29% may indicate unfavourable conditions for the water conservation strategy of the plant.

Adaptation mechanism

Overall, the analysis suggests that both plant type and season significantly influence several plant parameters. According to this study (Tables 3 and 4), regardless of the season, the majority of plant traits tend to exhibit moderate tolerance to the environmental conditions. This indicates a general adaptability of the plants to the prevailing conditions. However, there are variations in the number of highly tolerant and susceptible traits across different sampling units and seasons (Table 5). The table suggests that the tolerance and susceptibility of plants to different parameters vary between the summer and monsoon seasons. While some plants are tolerant of summer conditions, they may be susceptible to monsoon conditions, and vice versa. Tolerant plants generally had higher values. Susceptible plants had lower values for most parameters, indicating their sensitivity to summer and monsoon conditions (Tables 4, 5, and 6). This information can be useful for understanding plant adaptation strategies and for selecting suitable plant species for different environmental conditions.

Table 6: Tolerant and susceptible plants during summer & monsoon

	Tolerant plant		*Susceptible plant*	
Parameter	*Summer*	*Monsoon*	*Summer*	*Monsoon*
FW	1,8	7	-	-
TW	1,8	2,7	-	-
DW	1,8	7	-	4
RWC	1	3,7	7	1,8
LA	8	2,7	-	4
pH	4,5	6	-	4
EC	4,5	3	1	6
TDS	5	3,8	1	-
SD	2,7	4,8	4,8	3,6
TD	3,5	4,8	2,8	-
SC	8	8	1	-
NOL	3,8	3,5	-	7

Here, 1 to 4 are cultivated plants,5 to 8 are wild plants

Conclusion

This study unveiled significant seasonal influences on various morphological, physiological, and ecological parameters of *Madhuca indica* of Godhra situated in Panchmahal district of Gujarat. Based on response to seasonal fluctuations for particular trait plants were categorized as susceptible, moderately tolerant, or highly tolerant based on their response to seasonal fluctuations. Notably, wild plants demonstrated substantial variability in these parameters compared to cultivated plants. These findings align with previous research which indicated genetic variability among *M. indica* populations in the Panchmahal region. The observed parameter variations in the current study may be attributed to genetic diversity, which can influence plant responses to environmental factors, particularly during contrasting seasons like summer and monsoon. The varying correlation coefficients (R-values) between parameters during these seasons further supports the hypothesis that genetic variability plays a crucial role in shaping the phenotypic plasticity of *M. indica* plants.

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Author Contribution

Darshana Hirani conducted this research under the supervision of Dr. Rupesh Nakar, who also critically reviewed and approved it for publication. The authors jointly affirm their responsibility for the work's integrity and accuracy, including addressing any related inquiries.

Conflict of Interest

Authors state no competing interests.

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