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RESEARCH ARTICLE

Phenological Insights and Seed Trait Diversity in Fourteen Native Plant Species of Central India

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Abstract

Phenological events such as flowering, fruiting, and seed maturity are critical stages in the lifecycle of plants, playing a pivotal role in ecological processes and plantation programs. This study examines the phenological patterns and seed trait diversity of 14 native tree species from central India: *Buchanania cochinchinensis, Butea monosperma, Cochlospermum gossypium, Commiphora wightii, Feronia limonia, Hymenodictyon excelsum, Kydia calycina, Mallotus philippensis, Nyctanthes arbortristis, Putranjiva roxburghii, Pterospermum acerifolium, Semecarpus anacardium, Sterculia villosa,* and *Stereospermum chelonoides*. Conducted over three years (2021–2024) across diverse forested landscapes, the study identifies interspecific variation in flowering, fruiting, and seed maturation timelines. Using advanced image analysis, we quantified key morphometric parameters such as seed area, length, width, aspect ratio, average diameter, perimeter, convex perimeter, and roundness, alongside colorimetric attributes determined with the RHS color chart. The findings reveal a remarkable diversity in phenological and seed traits, offering valuable insights for ecological research, biodiversity conservation, and sustainable forest management. The outcomes of this study hold practical relevance for nursery managers, small-scale planters, and forest managers by providing critical information on fruiting periods and optimal seed collection timings for the propagation of desired tree species.

Keywords: Colorimetric analysis, Conservation biology, Ecological significance, Morphometric analysis, Phenology, Seed image analysis, Species diversity.

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Introduction

Phenological events such as flowering, fruiting, and seed maturation are critical determinants of reproductive success and long-term persistence in plant species. These events are closely regulated by environmental cues, including temperature, precipitation patterns, photoperiod, and biotic interactions (Heithaus, 1974; Frankie *et al*., 1975; Pulliam and Brand, 1975; Opler *et al*., 1976; Thompson and Willson, 1979; Stiles, 1980). In tropical and subtropical ecosystems, shifts in phenology due to climate variability can significantly alter reproductive timing, seed production, and subsequent seedling recruitment (Suresh and Sukumar, 2011).

Across Indian forest ecosystems, phenological studies have provided valuable insights into species-specific life history strategies. Research conducted in subtropical humid forests (Shukla and Ramakrishnan, 1982, 1984), Kumaun Himalayan forests (Ralhan *et al*., 1985; Pangtey *et al*., 1990), deciduous forests of Bandipur (Prasad and Hegde, 1986), and tropical moist forests of Karnataka (Bhat and Murali, 2001) has demonstrated that phenophases timing is not only taxon-specific but also responsive to microclimatic gradients and edaphic conditions.

Seed maturation represents a crucial terminal phenological stage, during which physiological and structural changes culminate in the attainment of maximum seed quality. Seeds harvested at physiological maturity generally exhibit superior viability and vigor, which are essential for successful germination and seedling establishment (Edwards, 1980; Singh and Kachari, 2006). Morphological markers, such as fruit dehiscence, color changes, and firmness, serve as practical indicators for determining the optimal harvest window (Piña-Rodrigues and Aguiar, 1993). Tools such as the Royal Horticultural Society (RHS) Color Chart enhance the accuracy of maturity assessment and have proven particularly useful in seed quality assurance protocols (Tucker *et al*., 1991; RHS, 2015).

Seed morphometric traits, including size, shape, and surface characteristics, are important predictors of germination performance and ecological adaptability. These traits often reflect the plant's reproductive strategy and its ability to respond to local environmental pressures (Dell'Aquila, 2006; Oliveira *et al*., 2012; Amulya *et al*., 2022; Panda *et al.,* 2023). In rare, endangered, and threatened (RET) species, analysing seed variability offers insights into population-level genetic diversity and potential resilience to habitat degradation (Brus *et al*., 2011; Santana *et al*., 2013; Costa *et al*., 2016; Khumaeva *et al*., 2016). Advanced image-based phenotyping technologies now allow for rapid, non-destructive, and reproducible assessment of seed traits, enabling large-scale evaluation and supporting conservation-oriented research (Varma *et al*., 2013; Kapadia *et al*., 2017).

Central India is a biodiversity hotspot, home to a diverse assemblage of native tree species with ecological, medicinal, and socio-economic value. However, the lack of comprehensive data on the phenological behaviour and seed characteristics of these species, particularly RET taxa, hampers the development of targeted conservation and propagation strategies. Addressing this gap, the present study examines the phenological patterns and seed trait diversity of 14 native forest tree species of Central India-*Buchanania cochinchinensis*, *Butea monosperma*, *Cochlospermum gossypium*, *Commiphora wightii*, *Feronia limonia*, *Hymenodictyon excelsum*, *Kydia calycina*, *Mallotus philippensis*, *Nyctanthes arbor-tristis*, *Putranjiva roxburghii*, *Pterospermum acerifolium*, *Semecarpus anacardium*, *Sterculia villosa*, and *Stereospermum chelonoides*.

The study was conducted over four years (2020–2024) across representative forest landscapes. By integrating phenological observations with morphometric seed trait analysis, this work aims to contribute actionable knowledge for conservation planning, species restoration, and nursery-based propagation. The outcomes are expected to support forest managers, nursery practitioners, and researchers in optimizing seed collection timings, enhancing seed handling protocols, and improving the quality of planting stock for afforestation and ecological restoration initiatives.

Materials and Methods

Study area

The study was carried out in the forested regions of Central India, encompassing diverse ecological zones characterized by varying climatic conditions, soil types, and altitudinal gradients. Central India experiences a tropical climate with distinct wet and dry seasons. Summers are hot, with temperatures ranging from 30 to 45°C, while winters are mild, with temperatures between 10 and 25°C. Annual rainfall ranges from 75–150 cm, predominantly during the monsoon season (June-September), followed by a prolonged dry period. The region is predominantly covered by tropical dry deciduous forests growing on red, black, and alluvial soils of moderate fertility. Its topography includes plateaus and ranges such as the Vindhyas and Satpuras, which create localized climatic variations. Field surveys were conducted across multiple districts to document the phenological and seed trait diversity of the following 14 native tree species: *B. cochinchinensis, B. monosperma, C. gossypium, C. wightii, F. limonia, H. excelsum, K. calycina, M. philippensis, Nyctanthes arbor-tristis, P. roxburghii, P. acerifolium, S. anacardium, S. villosa,* and *S. chelonoides*. Field observations were carried out over four years (2020–2024) to record phenological events, including flowering, fruiting, and seed maturation. Data were collected monthly to capture intra- and inter-annual variations. Phenophases were identified using morphological indicators such as flower bud development, fruit color changes, and seed dehiscence.

Seed collection and morphometric analysis

Seeds were collected during their maturation phase from multiple trees across different populations to ensure genetic diversity. Maturity was assessed using morphological indicators such as fruit size and color. To ensure precision in documenting fruit and seed colors, the RHS color chart was utilized. A minimum of 50 seeds per species per population were collected for morphometric analysis. Phenological observations revealed the following patterns:

Flowering period

The flowering period varied among species.

Fruiting period

Fruiting began soon after flowering, depending on the species.

Time of mature fruit/seed collection

Mature fruit and seed collection were recorded, varying by species.

Fruit color

Mature fruit colors documented using the RHS color chart ranged

Seed color

Seed collars, also recorded with the RHS color chart

Fruit maturity period (days)

The time from fruit initiation to physiological maturity, depending on the species.

Seed image analysis

An automated image analysis system (Biovis Seed Image Analyzer PSM 3000) was used to characterize the morphometric properties of Flacourtia indica seeds. This system employs a digital camera or flat-bed scanner to capture high-resolution images. During the analysis, seed samples were evenly distributed on a specialized measuring plane, ensuring consistent image capture under optimal lighting conditions to avoid shadows and reflections. The images were processed using dedicated software, which automatically measured various morphometric parameters such as seed area, length, width, aspect ratio, average diameter, perimeter, convex perimeter, and roundness. These parameters were then statistically analysed to identify significant differences between different seed size classes. Descriptive statistics (mean and standard deviation) were calculated for all measured parameters.

Results and Discussion

Fruit and seed maturity markers

The phenological patterns of 14 tree species show diverse flowering, fruiting, and seed maturation periods, along with variations in fruit and seed color (Table 1).

Flowering and fruiting

Flowering and fruiting periods varied widely across species. Some species, such as *C. wightii* and *F. limonia*, exhibited extended flowering periods, while others, including *B. monosperma* and *C. gossypium*, had more defined, shorter periods of flowering and fruiting.

Fruit and seed colors

The fruit colors ranged from shades of violet, orange, and red to brown and yellow, with notable differences in the RHS color groups used for observation. Seed colors ranged from white and yellow to black and dark brown, varying according to the species.

Fruit maturity period

The time to reach fruit maturity ranged from 60 days (e.g., *B. monosperma*, *C. gossypium*) to 340 days (e.g., *P. acerifolium*). Species like *F. limonia* had longer maturity periods (240–260 days), while others, such as *S. villosa* had quicker maturation (70–90 days).

These observations underscore the importance of understanding species-specific reproductive cycles for effective seed collection and management in conservation programs.

Image analysis

The seed morphometric observations for the fourteen study species, using the seed image analyzer, reveal notable variations in seed size and shape across the species. The following summary outlines key seed attributes (Fig. 1; Table 2).

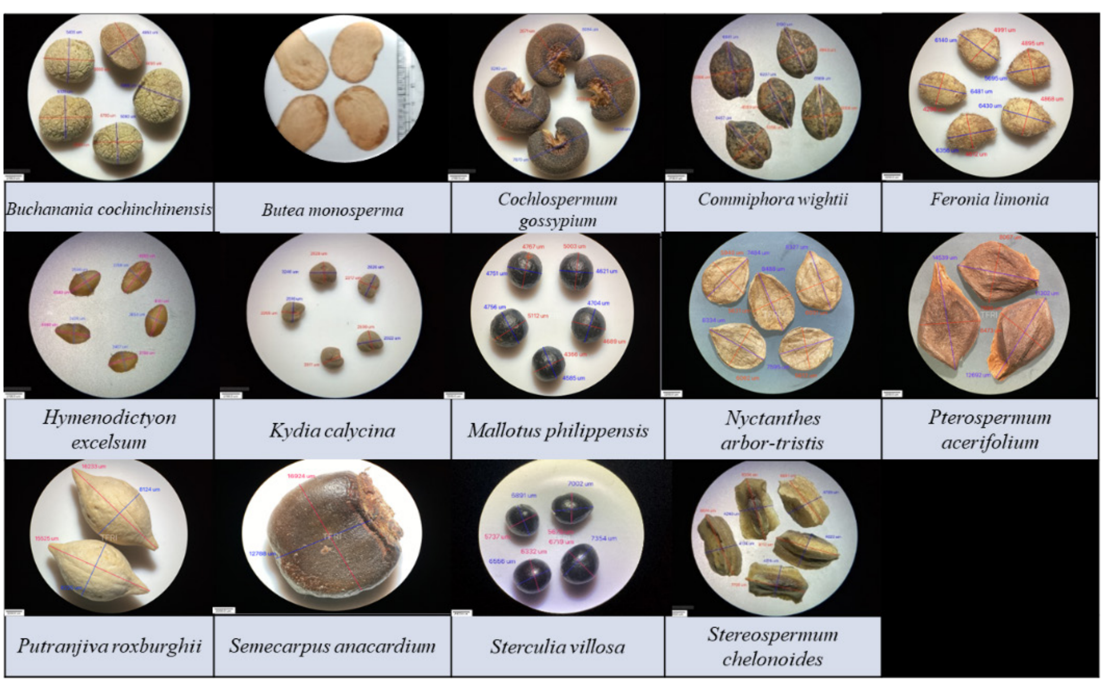

Fig. 1: Morphometric variability in seeds of the targeted plant species

Table 1: Phenological markers of fruit and seed maturity across native tree species

Species	*Flowering period*	*Fruiting period*	*Time of mature fruit/ Seed collection*	*Fruit color*	*Seed color*	*Fruit maturity period (Days)*
B. cochinchinensis (Lour.) Almei	Jan-March	April-May	May-June	Violet Blue Group N92 (Dark Greyish Purple A)	White Group155 (yellowish White A)	80–90
B. monosperma (Lamk.) Taub.	Feb-March	March-April	May-June	Greyed Orange Group 165 (Pale yellow D)	Greyed Orange Group 174 (Greyish Reddish orange B)	60–80
C. gossypium	Feb-March	March-April	April-May	Brown group (greyish reddish brown 200 B)	Brown Group 200 (Dark Greyish Reddish-Brown A)	60–80
C. wightii	Round the year	Oct-Nov	Nov-Dec, April-May	Red Purple Group 58 (Moderate purplish Red A)	Black group 203 (Black A)	90–120
F. limonia	Mar-April	Oct-Feb	Feb-March	Green white Group 157 (Pale Yellow Green B)	Greyed Orange Group 164 (Brownish Orange A)	240–260
H. excelsum	April-May	Jan-Feb	March-April	Greyed orange Group 177(Moderate Reddish Brown A)	Grayed orange Group N170 (Brownish Orange A)	140–160
K. calycina Roxb.	Aug-Oct	Sep-Dec	Jan-Feb	Greyed orange Moderate brown (165A)	Dark Greyed yellow N200A	90–110
M. philippensis (Lamk.) Mull-Arg.	Oct-Dec	Jan-Feb	Feb-March	Orange Red Group (Moderate Red N34 A)	Black group (Dark Greyish purple 202A)	140–170
Nyctanthes arbor-tristis (L.)	June-Sep	Sep-Oct	March-April	Greyed Orange Group 165 (Moderate Brown A)	Greyed brown group dark greyish yellowish (brown N199)	130–150
P. acerifolium (L.) Willd.	Mar-June	Apr-Sep	Dec-Feb	Grey brown Group 199 (Moderate Yellowish-Brown C)	Greyed Orange Group 177 (Moderate Reddish Brown A)	300–340
P. roxburghii Wall.	March-May	Feb-March	March- April	yellow group 8 Light greenish yellow C	Orange White Group159 (Pale Orange yellow C)	240–270
S. anacardium (L.) f.	April-Oct	Dec-March	April-May	Greyed Orange group N163 dark orange A	Black group 203 (Black D)	170–190
S. villosa	Aug-Sep	Oct-Nov	March-April	Red group strong reddish orange (42A)	Brown group dark greyish reddish brown (200A)	70–90
S. chelonoides	May-July	Oct-Dec	March-April	Grey brown Group 199(Light Olive Brown B)	Greyed Orange Group 164 (pale yellow D)	260–300

Area

The species with the largest seed area was *B. monosperma* (7.7255 ± 0.2913 cm^2), followed by *S. anacardium* (2.7311 ± 0.0846 cm^2), indicating that these species produce larger seeds compared to others, such as *H. orixense* (0.0080 ± 0.0253 cm^2), which has a notably small seed area.

Length and width

The longest seeds were observed in *B. monosperma* (3.8566 ± 0.0717 cm), with the widest being in *S. anacardium* (1.7920 ± 0.0264 cm). On the other hand, *H. orixense* had the smallest dimensions, both in length (0.3758 ± 0.0080 cm) and width (0.2405 ± 0.0072 cm).

Aspect ratio

The aspect ratio, indicating seed shape, was largest in *B. monosperma* (1.5097 ± 0.0338), suggesting a relatively elongated shape. In contrast, seeds of *H. orixense* and *K. calycina* had aspect ratios closer to 1, indicating more circular shapes.

Table 2: Seed morphometric observation in the targeted plant species using the seed image analyzer

Species	*Area (sq. cm)*	*Length (cm)*	*Width (cm)*	*Aspect (cm)*	*Diameter (Av cm)*	*Perimeter (cm)*	*Perimeter (Convex) (cm)*	*Roundness*
Buchanania cochinchinensis (Lour.) Almei	0.6886 ± 0.0245	1.0105 ± 0.0189	0.8954 ± 0.0187	1.1297 ± 0.0159	0.9084 ± 0.0172	3.1947 ± 0.0823	2.9693 ± 0.0515	0.8536 ± 0.0315
B. monosperma (Lamk.) Taub.	7.7255 ± 0.2913	3.8566 ± 0.0717	2.5579 ± 0.0551	1.5097 ± 0.0338	3.0974 ± 0.0591	10.8904 ± 0.2156	10.2987 ± 0.2096	0.8175 ± 0.0061
C. gossypium	0.3631 ± 0.0150	0.7337 ± 0.0192	0.6167 ± 0.0098	1.1884 ± 0.0170	0.6567 ± 0.0156	2.2492 ± 0.0574	2.1456 ± 0.0507	0.9005 ± 0.0113
C. wightii	0.2823 ± 0.0094	0.7035 ± 0.0186	0.5238 ± 0.0091	1.3467 ± 0.0424	0.5726 ± 0.0112	1.9700 ± 0.0378	1.8988 ± 0.0343	0.9123 ± 0.0084
F. limonia	0.3206 ± 0.0070	0.7864 ± 0.0117	0.5936 ± 0.0175	0.6337 ± 0.0069	0.5299 ± 0.0115	0.7738 ± 0.0122	2.3880 ± 0.0411	0.7119 ± 0.0196
H. excelsum	0.0080 ± 0.0253	0.3758 ± 0.0080	0.2405 ± 0.0072	1.5680 ± 0.0290	0.2950 ± 0.0074	1.0233 ± 0.0234	0.9763 ± 0.0228	0.8501 ± 0.0075
K. calycina Roxb.	0.0624 ± 0.0073	0.2753 ± 0.0068	0.2314 ± 0.0072	1.1953 ± 0.0185	0.2339 ± 0.0063	0.8071 ± 0.0205	1.0350 ± 0.0114	0.8648 ± 0.0191
M. philippensis (Lamk.) Mull-Arg.	0.1766 ± 0.0035	0.4838 ± 0.0063	0.4489 ± 0.0065	1.0790 ± 0.0065	0.4486 ± 0.0223	1.4988 ± 0.0048	1.4532 ± 0.0154	0.9888 ± 0.0054
Nyctanthes arbor-tristis L.	0.6067 ± 0.0205	1.0926 ± 0.0231	0.7886 ± 0.0144	1.3872 ± 0.0278	0.8713 ± 0.0138	3.2522 ± 0.1764	2.8798 ± 0.0512	0.7484 ± 0.0430
P. acerifolium (L.) Willd.	0.9766 ± 0.0287	1.5121 ± 0.0199	0.9417 ± 0.0153	1.6082 ± 0.0273	1.1098 ± 0.0165	3.9855 ± 0.0443	3.7468 ± 0.0433	0.7714 ± 0.0115
P. roxburghii Wall.	0.9713 ± 0.0454	1.4964 ± 0.0341	0.9861 ± 0.0263	1.5238 ± 0.0415	1.0951 ± 0.0247	4.5604 ± 0.1612	3.7840 ± 0.0766	0.5946 ± 0.0284
S. anacardium L. f.	2.7311 ± 0.0846	2.0854 ± 0.0414	1.7920 ± 0.0264	1.1634 ± 0.0161	1.8512 ± 0.0292	6.8140 ± 0.1660	6.0102 ± 0.0969	0.7438 ± 0.0253
S. villosa	0.3942 ± 0.0741	0.7447 ± 0.0797	0.6625 ± 0.0637	1.1240 ± 0.0516	0.6802 ± 0.0637	2.2680 ± 0.2127	-	0.9560 ± 0.2127
S. chelonoides	0.4351 ± 0.0253	0.9083 ± 0.0278	0.8202 ± 0.0266	1.1101 ± 0.0237	0.7374 ± 0.0210	2.9496 ± 0.0808	2.5441 ± 0.0729	0.6236 ± 0.0074

Diameter (average)

The species with the largest average seed diameter was *S. anacardium* (1.8512 ± 0.0292 cm), while *H. orixense* again had the smallest average diameter (0.2950 ± 0.0074 cm).

Perimeter

The species with the largest seed perimeter was *P. acerifolium* (4.5604 ± 0.1612 cm), while *H. orixense* had the smallest perimeter (1.0233 ± 0.0234 cm), correlating with its small seed size.

Convex perimeter

P. acerifolium also showed the largest convex perimeter (3.7840 ± 0.0766 cm), indicating a more irregular seed shape, while *H. orixense* again had the smallest value (0.9763 ± 0.0228 cm).

Roundness

M. philippensis had the highest roundness (0.9888 ± 0.0054), indicating nearly spherical seeds, while *P. acerifolium* exhibited the lowest roundness (0.5946 ± 0.0284), suggesting a less spherical, more elongated seed shape.

Overall, the data highlights the considerable diversity in seed size, shape, and other morphometric parameters across the fourteen species, with significant variability in seed dimensions, roundness, and perimeters. These variations may reflect different ecological adaptations or reproductive strategies within these species.

The phenological and seed morphometric data collected from the fourteen native tree species provide essential insights into their reproductive strategies and ecological adaptations, with potential implications for seed collection and conservation planning. The flowering and fruiting periods varied considerably among the species studied. For example, *C. wightii* and *F. limonia* exhibited extended flowering periods, potentially facilitating increased pollinator activity or optimized allocation of resources over time. In contrast, species like *B. monosperma* and *C. gossypium* displayed more synchronous and short flowering–fruiting cycles, which may be adaptive in seasonal environments to ensure reproductive success during limited windows of favourable conditions (Fenner, 1998).

Seed maturation periods also revealed significant interspecific variation. For instance, *F. limonia* demonstrated a longer seed maturation duration (240–260 days), whereas *S. villosa* matured seeds in 70–90 days. Such variation likely reflects species-specific ecological strategies and developmental physiology. Seed maturity indices, as emphasized by Edwards (1980) and Singh and Kachari (2006), are critical determinants of seed viability and germination potential. Our findings support this, as species with well-defined maturation periods tended to have higher germination rates and seedling vigor, emphasizing the importance of identifying species-specific collection windows to optimize propagation success.

Although environmental factors influencing seed maturation were not experimentally tested in this study, observational data and secondary literature indicate that temperature and soil moisture availability are key drivers (Piña-Rodrigues & Aguiar, 1993). This suggests the need for localized seed collection calendars that align with microclimatic conditions to enhance germplasm quality, especially under climate variability scenarios.

Fruit and seed color diversity observed among species may serve important ecological functions. Brightly colored fruits such as red, violet, and orange are generally associated with endozoochorous (animal-mediated) seed dispersal, particularly by birds and mammals (Howe & Smallwood, 1982). Seed morphometric traits-including size, shape, and roundness-also varied significantly among species. Larger-seeded taxa like *B. monosperma* and *S. anacardium* are presumed to allocate greater energy reserves to support initial seedling growth, a trait often associated with enhanced early survival (Westoby *et al*., 1996). Conversely, smaller-seeded species such as *H. orixense* appear to adopt a reproductive strategy favouring quantity over individual seed investment. Aspect ratio and roundness are associated with dispersal and germination behavior (Coomes & Grubb, 2003), and the variability noted among species supports the idea that seed morphology is tightly linked to adaptive reproductive ecology.

Seed image analysis was employed in this study as a modern tool to assess seed morphometry with greater accuracy and objectivity. Studies by Kapadia *et al*., (2017) and Dell'Aquila (2006) have demonstrated that image-based analysis can significantly improve precision in seed characterization. Our results corroborate these advantages, revealing clear associations between specific seed traits and predicted seed viability, germination success, and vigor. This suggests that imaging techniques can supplement traditional germination testing for quality assurance, particularly in large-scale seed programs.

Geographic and population-level differences in seed morphology were also evident, pointing to the influence of genotypic and environmental factors. Previous work by Brus *et al*., (2011) and Costa *et al*., (2016) has confirmed that local adaptation and population divergence contribute to variability in seed traits. While genetic analyses were beyond the scope of this study, the observed differences reinforce the importance of region-specific seed sourcing to maintain ecological suitability and adaptability in restoration efforts.

Conclusion

In conclusion, the study documents considerable variation in phenological and seed morphometric traits across fourteen native species of Central India. These differences reflect a spectrum of ecological adaptations, reproductive strategies, and dispersal mechanisms. By integrating maturity indices, environmental cues, and advanced tools such as seed image analysis, this research contributes to a deeper understanding of seed biology. Such insights are critical for developing informed strategies for conservation, restoration, and sustainable use of native flora, particularly under changing climate regimes and anthropogenic pressures.

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