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Phenological variation and seed maturity optimization for improved germination in *Mammea suriga* Kosterm. of the Central Western Ghats, India

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Abstract

Mammea suriga Kosterm. is an economically and ecologically important evergreen tree species of the Central Western Ghats, valued for its fragrant flowers and non-timber forest products. Despite its significance, limited information is available on its phenological behaviour and optimal seed maturity stage for successful regeneration. The present study was undertaken in evergreen to semi-evergreen forests of Uttara Kannada district, Karnataka, to examine phenological variation across seed sources and to identify the optimum fruit maturity stage for seed collection. Phenological observations were recorded at 15-day intervals on five morphologically superior trees selected from Sirsi and Hulekal forest ranges. Fruits were collected at four maturity stages—physical, physiological, harvest, and shedding stages—and seeds were evaluated for germination characteristics under nursery conditions using a Completely Randomized Design with three replications. Significant variation was observed among seed sources for both vegetative and reproductive phenological events, indicating provenance-level adaptation to local climatic conditions. Germination performance increased progressively with fruit maturity, with seeds collected at harvest maturity exhibiting the highest germination percentage (64%), germination value, and speed of germination. Seeds collected at premature and shedding stages showed reduced viability and vigor. The study highlights the importance of understanding phenological patterns and seed maturity indices for improving regeneration, nursery production, and sustainable utilization of *M. suriga* in conservation and afforestation programs.

Keywords: *Mammea suriga*, phenology, seed maturity, germination, Western Ghats, provenance variation, seed viability, regeneration

Introduction

India is one of the world's megadiverse countries, endowed with an extraordinary natural heritage represented by four global biodiversity hotspots: the Himalayas, Indo-Burma, Sundaland, and the Western Ghats. This remarkable diversity is reflected in its vast array of flora and fauna, high genetic variability, and significant levels of endemism. However, India's biological wealth is increasingly threatened by habitat destruction, overexploitation of natural resources, climate change, and the widespread introduction of exotic species (Totey *et al.*, 1989) ^[21]. Among various anthropogenic pressures, afforestation practices that rely heavily on exotic tree species to meet industrial demands have led to serious ecological consequences, particularly in sensitive ecosystems such as the Western Ghats. Climate-induced changes in species composition, phenological behavior, and ecological interactions further exacerbate conservation challenges, highlighting the urgent need for focused ecological research and evidence-based management strategies.

Phenology, the study of the timing of recurring biological events such as leaf flushing, flowering, fruiting, and seed dispersal, is a critical component of ecological and conservation research. Phenological patterns define life-cycle stages of tree species and strongly influence biodiversity maintenance, seed production, and forest productivity (Humberto *et al.*, 2014) ^[6]. In forest ecosystems, woody species pass through seedling, vegetative, and reproductive phases. Vegetative phenology includes leaf and stem growth, whereas reproductive phenology governs flowering, fruiting, and seed dispersal, all of which directly affect regeneration and population dynamics.

Phenological events are controlled by proximate factors such as temperature, rainfall, and photoperiod, as well as ultimate factors involving long-term evolutionary adaptations (Lobo *et al.*, 2003)^[10]. Altitudinal gradients significantly influence phenology, with species adjusting growth and reproductive cycles to maximize survival under varying climatic conditions (Ashton *et al.*, 1998; Lechowicz, 1984)^[2, 9]. Climate change has intensified phenological research, particularly in high-altitude and tropical ecosystems where shortened growing seasons increase species vulnerability (Walther *et al.*, 2002)^[22]. Understanding species-specific phenological responses is essential for predicting climate impacts, conserving ecological interactions, and managing genetic resources (Stern and Roche, 1974; Waser, 1979)^[19, 23]. Moreover, phenological studies provide insights into reproductive success, interspecific interactions, population stability, and ecosystem functioning (Newstrom *et al.*, 1994; Batalha & Martins, 2004)^[14, 3].

Seeds form the foundation of afforestation, restoration, and conservation programs. In India, demand for quality tree seeds has increased due to large-scale afforestation, land reclamation, and community forestry initiatives under the National Mission for a Green India (Shukla *et al.*, 2017)^[16]. Despite this, systematic documentation of species-wise seed demand remains inadequate (Thapliyal, 2014)^[20]. Seed quality depends on appropriate source selection, optimal timing of collection, careful handling, and proper storage to maintain viability and vigor. Seed maturity plays a decisive role in germination and seedling establishment, with fully mature seeds exhibiting superior longevity and vigor compared to immature ones (Willian, 1985). Inadequate seed handling and premature collection often result in poor plantation performance.

Mammea suriga Kosterm., commonly known as Suragi, is an economically and ecologically important tree species of the central Western Ghats, renowned for its highly fragrant flowers. These flowers are harvested annually between March and April and constitute an important non-timber forest product (NTFP). The species has multiple uses, including natural dye extraction, phytochemical and nanomaterial synthesis, ethnomedicinal applications, and essential oil production (Poojary *et al.*, 2015; Jadhav *et al.*, 2016)^[15, 7]. Dried Suragi flowers have significant commercial value and contribute substantially to rural livelihoods, generating export revenues between USD 2.2 and 4 million annually for farming communities in the Konkan region (Acharekar, 2021)^[1]. Despite its importance, Suragi regeneration is constrained by recalcitrant seed behavior, seasonal fruiting, and the absence of standardized nursery techniques. Given the growing demand for plant-based pharmaceuticals, perfumes, and flavor products, understanding phenology, seed biology, and regeneration dynamics of *M. suriga* is crucial for its sustainable conservation and utilization.

Methodology

The present investigation was conducted in evergreen to semi-evergreen forest ecosystems of the Central Western Ghats in Uttara Kannada district, Karnataka, India. The study sites included Chipagi, Kathgal, Yana, Manchikere, Ramanguli, Bhakkal, Sonda, Kumata, and Gerusoppa, where *Mammea suriga* occurs naturally. These locations represent the natural range of the species and encompass varying ecological and microclimatic conditions. Information on the distribution of *Mammea suriga* was obtained from regional floristic records. A preliminary field survey was carried out with the assistance of officials from the Forest Department and local residents to identify potential seed sources and assess seed availability. Based on species abundance

and accessibility, suitable provenances within the Central Western Ghats of Karnataka were selected for the study.

To study phenology and identify the optimal maturity stage for seed collection of *Mammea suriga*

To study phenological behavior and to determine the optimal stage of seed maturity, five morphologically superior *Mammea suriga* trees were identified in the Sirsi and Hulekal Forest Ranges of Uttara Kannada district. Phenological observations were recorded for each selected tree at 15-day intervals. Vegetative phenology included monitoring the period of leaf shedding, leafless duration, initiation of leaf flushing, and the time required for full leaf expansion. Leaf shedding was visually recorded from the onset of yellowing until complete leaf fall, while the duration of the leafless phase and subsequent leaf development was documented for each tree.

Flowering and fruiting phenology were recorded concurrently. Observations included flower bud initiation, complete blooming, initiation of fruit development, and fruit maturity. Fruits were collected at four distinct maturity stages, based on external colour and developmental characteristics: physical maturity (initial stage), physiological maturity, harvest maturity, and the fruit shedding stage. Seeds extracted from fruits at each maturity stage were sown in sand beds under nursery conditions to assess germination performance. The experiment was laid out in a Completely Randomized Design with three replications. Germination parameters such as germination percentage, germination value, speed of germination, daily germination speed, and number of daily counts were recorded starting from the date of first germination.

To assess morphometric traits of fruit, seed, and germination characterization in *Mammea suriga*

For morphometric characterization, twenty fruits were randomly selected from the seed lots of each population. Fruit length and thickness were measured using a digital vernier caliper, while fruit weight was recorded using a sensitive electronic balance. Similarly, twenty seeds were randomly selected to measure seed length, seed thickness, and seed weight, and mean values were calculated. These observations were used to assess variation in fruit and seed traits and their relationship with germination behavior.

Statistical analysis

The experiment was conducted using a Completely Randomized Design (CRD) with three replications. Germination and morphometric data were subjected to analysis of variance (ANOVA) to test the significance of differences among maturity stages. Germination percentage data were arcsine-transformed before analysis to normalize variance. Mean comparisons were performed using appropriate post-hoc tests at a 5 per cent level of significance. All statistical analyses were carried out using standard statistical software.

Results

To study phenology and identify the optimal maturity stage for seed collection of *Mammea suriga*.

Mammea suriga is an evergreen species, with no distinct leafless period, indicating continuous foliage retention (Table 01). Leaf flushing began in early January and took 10 days for completion. Flower bud initiation occurred in mid-February, and full blooming was completed by mid-March. Fruit initiation occurred by the end of March, with fruit maturity spanning April to May, indicating a slightly earlier reproductive phase.

The foliar phenological observations of *Mammea suriga* revealed significant variation among different seed sources (Table 01). Due to its semi-evergreen nature, the timing of leaf shedding could not be distinctly identified; however, clear differences were evident in dormancy and subsequent leaf development. The leafless period ranged from 11 days in the Bakkal source to 16 days in both Kumta and Sonda, indicating a 5-day variation among sources. The shorter leafless phase in Bakkal suggests a rapid initiation of new foliage, while the longer dormancy in Kumta and Sonda reflects a delayed transition to active growth. Intermediate durations were noted for Gerusoppa (12 days) and Kathagal (14 days). Similarly, leaf expansion duration varied from 9 to 13 days across seed sources. Kathagal recorded the shortest expansion period (9 days), followed by Gerusoppa (10 days), suggesting a faster rate of leaf development. Conversely, Bakkal showed the longest expansion (13 days), whereas Kumta and Sonda took 12 days each to attain full leaf size. The low standard error mean (0.22 and 0.324) and significant critical difference (CD = 2.153 and 1.89 at 5%) confirm consistent and statistically meaningful differences. Overall, these results highlight provenance-level variation in *M. suriga*, reflecting potential genetic differentiation and microclimatic adaptation among seed sources.

The reproductive phenological observations of *Mammea suriga* revealed significant variation among seed sources in the timing of flower bud initiation, blooming, fruit initiation, and fruit maturity (Table 02). Flower bud initiation ranged from 41 days in Bakkal to 58 days in Kumta, showing a clear 17-day difference among provenances. The earliest initiation in Bakkal and Sonda suggests early floral development, whereas delayed initiation in Gerusoppa and Kumta indicates later reproductive onset. Complete blooming also varied considerably, occurring earliest in Bakkal (70 days) and latest in Kumta (91 days), implying that coastal seed sources flower earlier than inland ones, possibly due to differences in humidity, temperature, and rainfall patterns. Fruit initiation followed a similar sequence, ranging from 86 days in Bakkal to 101 days in Kumta. Early-flowering sources such as Bakkal and Sonda also initiated fruiting earlier, suggesting a consistent reproductive rhythm. Fruit maturity varied from 104 days in Kathagal to 126 days in Kumta, highlighting shorter fruit development periods in early-flowering sources. Bakkal and Kathagal exhibited early and rapid reproductive progression, whereas Kumta showed delayed and prolonged development,

reflecting genotypic variation and environmental adaptation influencing reproductive phenology in *M. suriga*.

The germination characteristics of *Mammea suriga* exhibited pronounced variation among different stages of fruit maturity in terms of germination percentage, germination value, speed of germination, and daily germination speed (Table 02). The germination percentage increased substantially with advancing fruit maturity, indicating a strong influence of seed developmental stage on germination performance. Seeds collected at the physical maturity stage recorded the lowest germination percentage (15%), while those at physiological maturity showed moderate improvement (28%). The highest germination percentage (64%) was recorded at the harvest maturity stage, followed by a slight decline at the shedding stage (56%). This pattern suggests that seeds attain maximum viability and vigor at harvest maturity, whereas extended retention on the mother tree may cause over-maturity and a marginal reduction in germination.

The germination value, which integrates both speed and completeness of germination, also followed a similar trend. It increased progressively from 3.98 at physical maturity to 4.55 at physiological maturity, peaking at 5.28 during harvest maturity. A slight reduction was observed at the shedding stage (4.91). The results indicate that harvest maturity represents the physiological optimum stage for obtaining seeds of superior quality, characterized by higher viability and uniform germination. The speed of germination also improved as the fruits matured, increasing from 1.74 at physical maturity to 1.89 at harvest maturity, followed by a slight reduction to 1.81 at the shedding stage. Similarly, the daily germination speed rose from 1.81 at physical maturity to 1.94 at harvest maturity, showing a small decrease to 1.93 during the shedding stage. These results emphasize that seed vigor and germination rate are highest when fruits are harvested at their optimum maturity rather than after natural shedding. The findings clearly demonstrate that fruit maturity stage significantly affects the germination behaviour of *Mammea suriga*. Seeds collected at the harvest maturity stage exhibited the highest germination percentage, vigor, and rate, highlighting it as the optimum stage for seed collection. Conversely, seeds collected either prematurely (physical or physiological maturity) or after shedding showed reduced performance, likely due to incomplete seed development or onset of deterioration during prolonged attachment to the parent tree

Table 1: Foliar phenological events (Days) as influenced by different seed sources of *Mammea suriga* (in days)

Seed Source	Time of leaf shedding	Leafless period	Time of leaf flushing initiation	Leaf Expansion Duration	Flower Bud Initiation	Complete Blooming	Initiation of Fruiting	Fruit Maturity
	Not specific	Evergreen	January	10 days	Mid-February	Mid-March	March-end	April-May
Kumta	NA	NA	16	12	58	91	101	126
Gerusoppa			12	10	49	78	89	114
Kathagal			14	09	45	73	90	104
Bakkal			11	13	41	70	86	112
Sonda			16	12	43	75	87	108
SEM			0.22	0.324	0.251	0.110	0.314	0.147
CD 5%			2.153	1.89	2.157	2.68	3.21	3.421

Table 2: Variation in germination among different stages of fruit maturity in *Mammea suriga*

	Germination percentage	Germination value	Speed of germination	Daily germination speed
Physical maturity	15.00	3.98	1.74	1.81
Physiological maturity	28.00	4.55	1.78	1.88
Harvest maturity	64.00	5.28	1.89	1.94
Shedding of fruits	56.00	4.91	1.81	1.93
SE(m) ±	0.311	0.214	0.015	0.112
CD@ 5%	3.251	0.054	0.024	0.032

Discussion

The phenological assessment of *Mammea suriga* reveals clear distinctions in their growth cycles and reproductive strategies, reflecting adaptations to their respective ecological niches. Such variation likely reflects genotypic diversity and local adaptation to climatic regimes, particularly to differences in the onset of dry periods and temperature fluctuations (Nanda *et al.*, 2014) ^[13]. The observed foliar phenological variations among the seed sources of *Mammea suriga* suggest clear provenance-level differentiation in growth rhythm and dormancy patterns. Although the species exhibits a semi-evergreen habit, significant differences were recorded in the duration of the leafless period and leaf expansion, indicating genetic and environmental influences on phenological behaviour (Singh & Kushwaha, 2005) ^[18]. The shorter leafless phase in the Bakkal source (11 days) compared to the longer dormancy observed in Kumta and Sonda (16 days) suggests that Bakkal trees resume vegetative activity earlier, possibly in response to favourable local climatic cues such as higher soil moisture or humidity (Morellato *et al.*, 2000) ^[12]. The shorter expansion period in Kathagal (9 days) and Gerusoppa (10 days) suggests a higher rate of leaf growth and metabolic efficiency, consistent with findings that phenological timing is closely linked to resource availability and microclimatic conditions.

Sundarapandian *et al.* (2005) studied vegetative and reproductive phenology of 42 tree species of tropical forest at Kodayar in the Western Ghats, Tamil Nadu. The study concluded that phenological behaviour displayed by the tree was found to be an adaptation to the surrounding abiotic and biotic environment. *M. suriga* is evergreen, retaining its foliage throughout the year, which enables continuous photosynthetic activity and growth. The initiation of leaf flushing also differed between the species. *M. suriga* initiated flushing in January. Furthermore, *M. suriga* exhibited a shorter leaf expansion duration (10 days), indicating a more rapid canopy regeneration. This accelerated leaf development in *M. suriga* may support its early flowering and fruiting phases, which in turn could be advantageous in maximizing reproductive success before peak summer stress (Singh & Kushwaha, 2005; Borchert *et al.*, 2005) ^[18, 4]. Menzel *et al.* 2006 ^[11], concluded that advancement and delay in phenological events were responsive to temperature.

The significant differences in flower bud initiation, blooming, fruit initiation, and fruit maturity suggest that each provenance responds differently to local climatic cues such as temperature, humidity, and photoperiod (Morellato *et al.*, 2000) ^[12]. The early initiation of flowering and fruiting observed in the Bakkal and Sonda sources suggests their adaptation to relatively warmer and humid microclimates, which may promote earlier bud differentiation and floral induction in *M. suriga*. Conversely, the delayed reproductive events in Kumta may reflect environmental constraints such as lower temperature or delayed onset of favorable conditions for flowering. Phenological variation plays a crucial role in reproductive success and synchronization with pollinators (Kallarackal and Renuka, 2014) ^[8]. Earlier flowering sources may gain a competitive advantage through better pollination efficiency and fruit set, while delayed flowering sources could be prone to reduced reproductive efficiency due to asynchronous phenology.

The timing of reproductive events also varied significantly. *M. suriga* displayed an earlier flowering cycle, with bud initiation in mid-February and blooming completed by mid-March. This shift in phenophase timing continued into the fruiting stage. *M. suriga* began fruiting by the end of March and reached maturity between April and May. The evergreen habit and early reproductive cycle of *M. suriga* suggest an adaptation toward maximizing resource

utilization year-round, especially under relatively stable environmental conditions. The climate conditions also affected the phenological character of *Rhododendron arboreum* in central Himalaya (Singh *et al.*, 2014) ^[17]. Similarly, Gordo and Sanz (2010) ^[5] had concluded that climate change had shifted the plant phenology in the Mediterranean region. Such phenological insights are vital for understanding species' responses to climatic variables, predicting their resilience under changing environmental conditions, and guiding conservation, management, and agroforestry practices.

Conclusion

The present study demonstrates that *Mammea suriga* exhibits distinct provenance-level variation in vegetative and reproductive phenology across the Central Western Ghats, reflecting genetic differentiation and adaptation to local microclimatic conditions. The species maintains an evergreen to semi-evergreen habit with early leaf flushing and reproductive onset, enabling efficient resource utilization throughout the year. Significant differences in flowering and fruiting phenophases among seed sources emphasize the role of climatic cues such as temperature, humidity, and rainfall in regulating phenological behaviour. Seed maturity stage was found to be a critical determinant of germination success in *M. suriga*. Seeds collected at the harvest maturity stage showed superior germination percentage, vigor, and germination rate compared to seeds collected at earlier or later stages. Premature collection resulted in poor germination due to incomplete seed development, while delayed collection after fruit shedding led to reduced viability, likely due to onset of deterioration. These findings establish harvest maturity as the optimum stage for seed collection in *M. suriga* and underscore the need for species-specific phenological and seed biology studies to support effective nursery practices, afforestation, and restoration efforts. The study provides valuable baseline information for conservation planning, sustainable utilization, and enhancement of planting stock quality for this high-value NTFP species of the Western Ghats.

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