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Assessing the climate suitable regions using ecological niche modelling for the cultivation of phalsa, an underutilized fruit in India

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ABSTRACT

Phalsa an underutilized fruit-bearing shrub of the family Malvaceae, possesses immense potential for diversification of sustainable horticulture and nutritional security, particularly in marginal and degraded lands yet remains neglected in mainstream horticulture. The present study assessed the potential climatic suitability of phalsa cultivation in India using Ecological Niche Modelling (ENM) based on the Maximum Entropy (MaxEnt) algorithm integrated with DIVA-GIS. Seventy-five geo-referenced occurrence points were collected from six districts of Telangana, representing semi-arid agro-ecosystems, and analyzed with nineteen bioclimatic variables derived from WorldClim data. The results identified extensive regions in central, southern, and eastern India particularly Telangana, Andhra Pradesh, Karnataka, Maharashtra, Madhya Pradesh, and Odisha as highly to moderately suitable for phalsa cultivation. The most influential environmental variable was precipitation of the driest month (Bio14). The findings provide a scientific basis for crop diversification, regional planning, and conservation strategies aimed at promoting phalsa cultivation in India's changing climatic context.

Key words: DIVA-GIS, germplasm, vegetative pattern, ecological niche modelling, MaxEnt.

INTRODUCTION

Phalsa (*Grewia asiatica* L.), commonly called star apple, belongs to the genus *Grewia* within the family Malvaceae (formerly Tiliaceae) (Ghosh *et al.,* 3). The genus *Grewia*, comprising about 150 species ranging from small shrubs to trees, is widely distributed across tropical and subtropical regions of the world (Youngken, 25). It was named in honor of Nehemiah Grew, a pioneer in the field of plant physiology. Most *Grewia* species are wild and highly valued for their multipurpose uses as sources of fodder, fuelwood, timber, craft materials, and medicinal ingredients (Sharma and Patni, 17). Notably, Grewia is the only genus within the Tiliaceae family that bears edible fruits (Zia-ul-Haq *et al.,* 26), among which *G. asiatica* and *G. tenax* are the most commonly cultivated for their fruit value (Youngken, 25).

Phalsa is believed to have originated in South Asia and is now widely distributed in subtropical and tropical regions across the globe. The major phalsa-producing countries include India, Pakistan, Sri Lanka, the Philippines, and Bangladesh. In India, it is found in central and southern regions, as well as the western Himalayas up to elevations of about 3000 feet (Sastri *et al.,* 15). Phalsa is cultivated in West Bengal, Haryana, Rajasthan, Punjab, Andhra Pradesh, and Tamil Nadu. In Punjab, approximately 30 hectares are under phalsa cultivation, yielding about 196 tonnes per hectare annually. The crop is known by various local names, including Phalsa (Hindi, Urdu, Marathi), Phulsa (Kannada), Shukri (Gujarati, Bengali), and Unnu (Tamil).

Phalsa is an underutilized fruit-bearing shrub known for its small drupaceous fruits, which exhibit significant medicinal and nutritional value. The fruits are typically purple and may turn black upon full ripening. A variety of bioactive compounds, including polyphenols, flavonoids, anthraquinones, saponins, and coumarins, contribute to its therapeutic potential (Sharma and Patni, 17). The ripe fruits contain 50–60 percent juice, with sugar levels ranging from 10–11 percent and acidity between 2.0–2.5 percent, and serve as a rich source of vitamins A and C. They are low in calories and fat but high in minerals and dietary fiber. Phalsa also provides appreciable amounts of phosphorus (24.2 mg/100 g) (Yadav, 24) and iron (140.8 mg/100 g fresh fruit weight) (Khan *et al.,* 5). Due to their perishable nature, the ripe fruits are usually consumed fresh or processed into soft drinks such as squashes, juices, and syrups. The fruits are traditionally consumed during summer for their cooling effect on the body.

Phalsa is highly valued in traditional medicine for its diverse therapeutic properties. It has been used to treat diarrhea, jaundice, stomach and intestinal disorders, cough, fever, wounds, skin diseases, and osteoporosis (Khemiss et al., 6; Kshirsagar and Upadhyay, 7; Sharma and Patni, 17; Sinha *et al.,* 18). The fruits possess cooling and astringent qualities; unripe ones help relieve inflammation and respiratory,

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*Corresponding author email: p.pranusha@icar.org.in; pranushaag@gmail.com circulatory, and febrile conditions (Morton *et al.,* 9). Phalsa is also beneficial for liver and heart ailments, indigestion, toxemia, asthma, and diabetes due to its low glycemic index. Leaf and fruit extracts exhibit strong antioxidant, anticancer, and hepatoprotective effects (Tiwari *et al.,* 21; Asghar *et al.,* 2; Sharma and Sisodia, 16). The root bark is used for rheumatism, and leaf infusions are applied for skin blemishes.

Phalsa thrives in hot summers and enters dormancy during winter, shedding its leaves. New shoots emerge in spring as temperatures rise. High temperatures accelerate fruit ripening and maturation. Phalsa can grow on low-fertility barren soils, well-drained loamy soil with a pH between 6.1 and 6.5 is ideal for achieving optimal growth, yield, and fruit quality. However, phalsa is a perishable fruit with a shorter shelf-life of about 1–2 days after harvest, due to which there is very less time for further processing. So, served as suitable only for local marketing.

Phalsa, despite its exceptional nutritional composition, rich ethnomedicinal heritage, and proven pharmacological potential, remains a neglected and underutilized fruit crop. The major constraints limiting its wider adoption include small fruit size, extended ripening duration, repeated harvesting needs, and high perishability. Additionally, inadequate market awareness, poor post-harvest infrastructure, and the absence of organized cultivation programs have further restricted its commercialization. Given the growing emphasis on sustainable agriculture and crop diversification, phalsa holds significant potential as a climate-resilient horticultural crop for marginal and degraded lands, meriting greater research attention and industrial investment.

Underutilized fruit crops such as phalsa hold substantial potential to enhance nutritional security, particularly in marginal and resource-limited regions where conventional staple crops perform suboptimally. Unlocking this potential necessitates a comprehensive understanding of the species' climatic requirements, which can be effectively assessed using Ecological Niche Modelling (ENM). Among the available ENM approaches, the Maximum Entropy (MaxEnt) algorithm has proven to be a robust and widely adopted method for predicting species distributions based on presence-only data (Phillips *et al.,* 11). The utility of MaxEnt has been demonstrated in modeling suitable agro-climatic zones for several crops, including roselle and sorghum (Sivaraj *et al.,* 20). In the present investigation, MaxEnt-based ENM integrated with DIVA-GIS was utilized to delineate and spatially map climatically suitable regions for phalsa cultivation across India. The findings from this study are expected to support micro-level agricultural planning, promote sustainable horticultural diversification, and contribute to the conservation and effective utilization of this underexploited yet climate-resilient fruit species. The specific objectives of the study were to evaluate the climatic suitability of phalsa across India, identify potential areas for the expansion of its cultivation, and facilitate the development of conservation and sustainable utilization strategies.

MATERIALS AND METHODS

A total of 75 geo-referenced occurrence points of phalsa were collected from six districts of Telangana Hyderabad, Mahaboobnagar, Medak, Nalgonda, Nizamabad, and Ranga Reddy through field surveys and the ICAR-NBPGR germplasm database (Sivaraj and Pandravada, 19). These points represented the observed natural and cultivated presence of phalsa populations in semi-arid ecosystems. Climate dataset grids from the WorldClim (WC) database sourced (http://www.worldclim.org) from global weather stations is downloaded and further used in this study. The World Clim data provides interpolated global climate surfaces using independent variables (latitude, longitude, and elevation) and represents long-term (1950-2000-current & future) monthly means of maximum, minimum, mean temperatures and total precipitation as generic 2.5 arc-min grids. All layers were prepared as 2.5 arc-minute resolution grids in ASCII format for model input. Environmental layers used (all continuous) for this study: bio1 (Annual mean temperature); bio2 (Mean diurnal range); bio3 (Isothermality); bio4 (Temperature seasonality); bio5 (Max. temperature of warmest month); bio6 (Min. temperature of coldest month); bio7 (Temperature annual range); bio8 (Mean temperature of wettest quarter); bio9 (Mean temperature of driest quarter); bio10 (Mean temperature of warmest quarter); bio11 (Mean temperature of coldest quarter); bio12 (Annual precipitation); bio13 (Precipitation of wettest month); bio14 (Precipitation of driest month); bio15 (Precipitation seasonality); bio16 (Precipitation of wettest quarter); bio17 (Precipitation of driest quarter); bio18 (Precipitation of warmest quarter); bio19 (Precipitation of coldest quarter). The MaxEnt model estimates an unknown probability distribution that "satisfies any constraints on the unknown distribution that we are aware of, and that subject to those constraints, the distribution should have maximum entropy" (Phillips *et al*., 11). In information theory, entropy is randomness or unpredictability, meaning that the portion that is not explained by the probability distribution has no remaining information with respect to the distribution of the prior data. This study utilized the geo-referenced occurrence locations and climatic grid data for the *phalsa* fruit presence points (75 presence points) from 6 districts of Telangana state and analyzed information about environmental conditions at the current locations of phalsa to assess the probability of suitable conditions existing for the cultivation of this important underutilized fruit. DIVA-GIS version 7.5 downloaded from www.diva-gis.org was used to generate the final map (ecological niche models) based on the output generated from (asci file) the operation of MaxEnt software.

RESULTS AND DISCUSSION

Phalsa is a scraggly shrub or small tree to 15 ft (4.5 m) or more. The phalsa has long, slender, drooping branches, the young branchlets densely coated with hairs. The alternate, deciduous, widely spaced leaves are broadly heart-shaped or ovate, pointed at the apex, oblique at the base, up to 8 inch (20 cm) long and 6 1/2 inch (16.25 cm) wide, and coarsely toothed, with a light, whitish bloom on the underside (Fig.1). Small, orange-yellow flowers are borne in dense cymes in the leaf axils. The round fruits, on 1 inch (2.5 cm) peduncles are produced in great numbers in open, branched clusters. The skin turns from green to purplish-red and finally dark-purple or nearly black. It is covered with a thin, whitish bloom and is thin, soft and tender. The soft, fibrous flesh is greenish-white stained with purplish-red near the skin. The flavour is pleasantly acid, somewhat grapelike. Large fruits have 2 hemispherical, hard, buff-coloured seeds 5 mm wide. Small fruits are single-seeded. Diversity exists in habit (shrub/tree), leaf curl (inward/outward), shape (cordate/ovate) and size (medium to large), stem colour (grey/black), fruit shape, pulp colour (green/pink/white), seed colour (pink, yellow, white), shape (spherical/flat) seeds per fruit (1-3), taste (sweet, sour), quality and yield (Sivaraj and Pandravada, 19).

Fig. 1. Phalsa habit (inset: Flowers in cymes and immature green fruit).

Phalsa an indigenous underutilized is grown in fewer pockets in India and the area is dwindling day by day. Sivaraj and Pandravada,19 collected 75 germplasm accessions from parts of Telangana (Table 1). The geographical coordinates recorded during the survey were used for developing the ecological niche model. Seventy-five geo-referenced occurrence points of *Grewia asiatica* were recorded across six districts of Telangana state Hyderabad, Mahaboobnagar, Medak, Nalgonda, Nizamabad, and Ranga Reddy (Table 1). The majority of accessions originated from Ranga Reddy (31 points) and Mahaboobnagar (17 points). These locations appropriately represent differing microclimatic conditions typical of semi-arid southern India. The field observations revealed distinct morphological diversity among accessions in terms of plant habit (shrub/tree form), leaf morphology, fruit shape, and pulp color in the initial studies conducted by Sivaraj and Pandravada, 19. Such phenotypic variability highlights the existence of considerable genetic diversity within the local germplasm pool. Phalsa's ability to thrive under high temperature fluctuations, moderate precipitation, and poor soil conditions underscores its suitability for arid horticultural systems. The observed natural adaptation in Telangana reinforces the importance of identifying broader regions across India that exhibit similar climatic characteristics for potential cultivation expansion.

The MaxEnt (Maximum Entropy) model is a widely accepted method for predicting species' potential geographic distributions by integrating occurrence records with environmental and climatic variables (Li *et al.,* 8; Qin *et al.,* 12; Sivaraj *et al.,* 20). Using species occurrence and bioclimatic data, it identifies areas favorable for their survival and spread under current and future climate conditions. The global ecological niche model (Fig. 2) generated using MaxEnt indicated that *Grewia asiatica* possesses a wide climatic tolerance, with potential cultivation zones extending across tropical and subtropical belts. The model predicted highly suitable regions in

Table 1: Geolocations surveyed sites of phalsa occurrence in Telangana.

District	Presence points
Hyderabad	3
Mahaboobnagar	17
Medak	15
Nalgonda	8
Nizamabad	1
Ranga Reddy	31

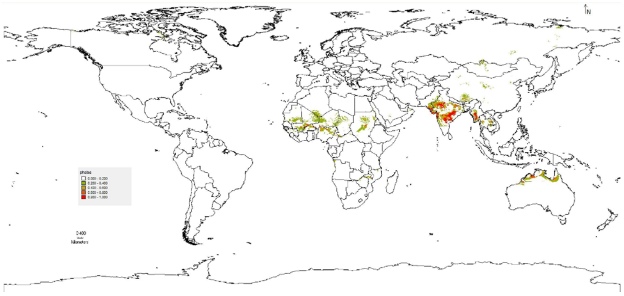

Fig. 2. Climatic suitable locations around the world for phalsa cultivation as indicated by MaxEnt model.

southern and eastern Asia (India, Pakistan, China, Myanmar, Laos, and Cambodia), several African nations (Angola, Chad, Mali, Nigeria, Sudan, and Zimbabwe), parts of Australia, and isolated zones in the Middle East (Saudi Arabia) and southern Russia. This distribution reflects the species' adaptability to environments characterized by warm temperatures and moderate seasonal rainfall. The global results validate earlier reports that phalsa performs optimally under mean annual temperatures of 20–32 °C and rainfall ranging from 500–1000 mm. Beyond its native range, the predicted global suitability zones indicate potential for introduction and adaptation trials in ecologically comparable environments, particularly in Africa and Southeast Asia. The MaxEnt-derived ecological niche map for India (Fig. 3) revealed high and moderate suitability zones were found through central, southern, and eastern belts for phalsa cultivation. High and moderate suitability zones were predicted across central and peninsular India, encompassing Andhra Pradesh, Telangana, Karnataka, Goa, Maharashtra, Odisha, Bihar, Jharkhand, Rajasthan, Gujarat, Madhya Pradesh, Uttar Pradesh, and West Bengal. The model highlights that phalsa can thrive in both semi-arid and sub-humid zones, aligning with its drought-tolerant and low-input nature. The central and western states, with well-drained soils and prolonged dry seasons, offer particularly promising conditions for its expansion. In contrast, regions with excessive humidity or waterlogging showed lower suitability scores. Such predictive maps serve as valuable decision-support tools for agricultural planners to prioritize specific districts for crop diversification programs. They can also guide germplasm conservation efforts by identifying zones of climatic congruence with native populations, thereby supporting *ex situ* and *in situ* conservation strategies.

Climate strongly influences plant distribution, vegetation patterns, and community structure. The Jackknife test of variable importance (Fig. 4) provided insights into the relative contribution of climatic factors influencing phalsa's potential distribution. Among the nineteen bioclimatic variables analyzed, "precipitation of the driest month" (Bio14) emerged as the most significant predictor, exhibiting the highest training gain when used in isolation. This finding emphasizes the crop's sensitivity to extreme dry-season moisture deficits. Phalsa's physiological resilience allows it to withstand limited water availability; however, complete aridity during flowering or fruiting can adversely affect yield and

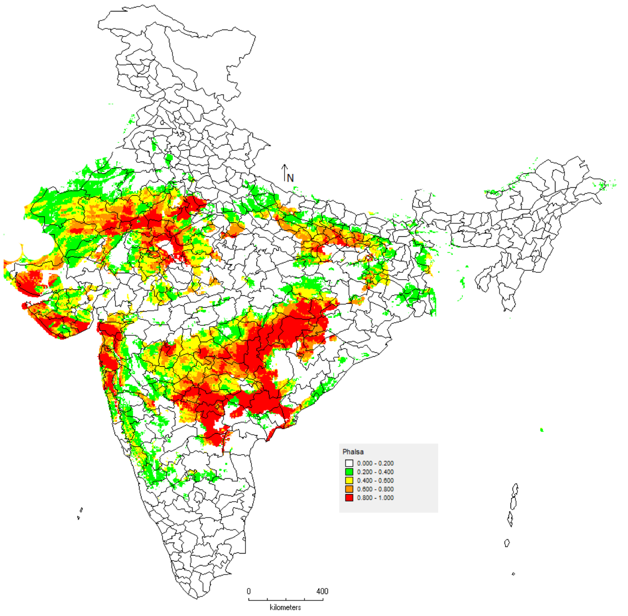

Fig. 3. MaxEnt ecological niche model showing phalsa's habitat suitability in India.

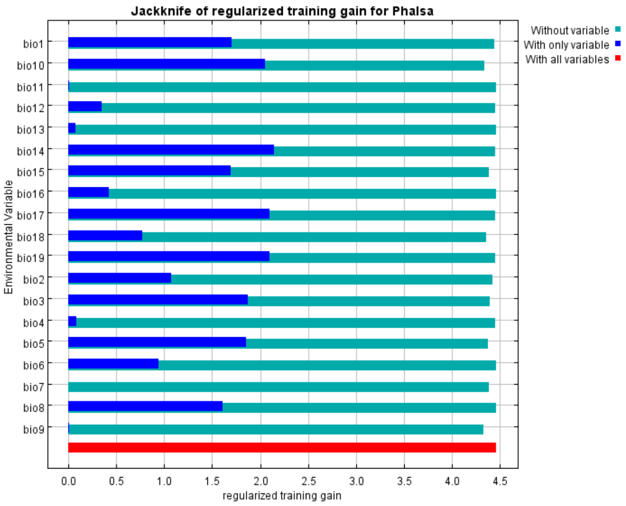

Fig. 4. Jackknife analysis of predictor variable importance in phalsa MaxEnt model.

fruit quality. Other influential parameters included are bio17 (Precipitation of driest quarter), bio19 (Precipitation of coldest quarter) and bio10 (Mean temperature of warmest quarter). Collectively, these variables explain the crop's preference for warm, moderately dry regions with distinct seasonal variations a pattern characteristic of most arid-zone fruit crops. The predominance of precipitation-based variables corroborates observations by Reddy *et al*., 13. for *Hibiscus sabdariffa* and by Sivaraj *et al*., 20 for sorghum landraces, where water availability during critical phenological stages was a key distribution determinant.

The model evaluation metrics demonstrated a high degree of accuracy and robustness. The fraction of background predicted (red curve) declines sharply with increasing threshold values, indicating minimal overprediction and a high level of selectivity in identifying potential habitat areas (Fig. 5). The omission rate for training samples (blue curve) remains low and consistently below the predicted omission line (black line), demonstrating a strong model fit and accurate capture of presence locations used during calibration. Although the omission rate for test samples (cyan curve) is slightly higher, it remains close to the expected omission, reflecting good model transferability and reliable performance on independent data. Collectively, these patterns confirm that the model performs significantly better than random, accurately characterizing the ecological niche of Phalsa and providing a robust basis for delineating climatically suitable regions for its cultivation. The inclusion of 75 presence points across variable climatic zones provided sufficient representation of phalsa's ecological amplitude, allowing the MaxEnt algorithm to generalize effectively across the Indian subcontinent.

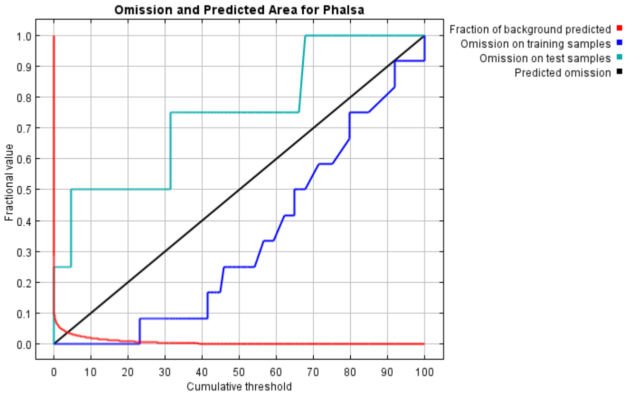

Fig. 5. Omission rate and predicted area as a function of the cumulative threshold for current climatic scenario in phalsa.

Climate change, through its multifaceted biotic and abiotic stresses, poses a substantial threat to the future of food crop production in India. Rising temperatures, erratic rainfall, and increasing pest and disease pressures have made it increasingly difficult to sustain agricultural productivity. In this context, phalsa emerges as a promising crop for diversification and sustainability due to its adaptability to marginal and degraded lands. With over 120 million hectares of such degraded land available in the country, phalsa cultivation could contribute significantly to climate-resilient and sustainable agricultural systems when supported by appropriate mitigation and adaptation strategies. The suitability of the cultivation site plays a crucial role in determining crop productivity. Site suitability maps derived from ecological niche or climatic modeling help identify the most favorable areas for successful cultivation. These maps serve as essential tools for planning and decision-making, enabling researchers and policymakers to focus on regions with the highest potential for crop establishment and yield stability (Parthasarathy *et al.,* 10). A range of site suitability and climate modeling approaches has been effectively employed to assess the potential impacts of climate change on shifts in crop production zones and growing regions (Parthasarathy *et al.,* 10; Sivaraj *et al.,* 20; Tubiello *et al.,* 22). These models aid in understanding the dynamics of crop–climate interactions and provide insights into future challenges and opportunities. Accordingly, it becomes imperative to develop and implement on-farm conservation strategies for phalsa in the regions identified as climatically suitable. Such initiatives would not only support the preservation of genetic diversity but also enhance the livelihood security of farmers through the promotion of a hardy, nutrient-rich, and climate-resilient fruit crop suitable for India's changing environmental conditions.

Phalsa, though underexploited, represents a valuable climate-resilient fruit crop suited to India's semi-arid and sub-humid regions. The MaxEnt-based ENM model effectively delineated the area's most suitable for its cultivation, offering an evidence-based framework for crop diversification and conservation planning. Given its resilience to drought, nutritional richness, and suitability for degraded lands, phalsa represents a promising crop for climate-smart horticulture and agricultural diversification. Strategic interventions including site-specific cultivation planning, germplasm conservation and value chain development are essential to promote its wider adoption, ensuring sustainable livelihoods and contributing to climate-resilient agricultural systems in India.

AUTHOR'S CONTRIBUTION

Conceptualization of research (PP, NS, SRP); Analysis of data and interpretation (NS, PP); Preparation of manuscript (PP); Manuscript review and editing (PP, NS, SRP).

DECLARATION

All authors agree to publication and any conflict as interest in the manuscript.

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