



The Miracle Fruit in a Hard Shell: Exploring the Potential of Bael (*Aegle marmelos* (L.) Corrêa)

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Highlight

- Bael (*Aegle marmelos* (L.) Corrêa) is an indigenous fruit tree of the Indian subcontinent with nutritional, cultural, ecological and ethnomedicinal importance.
- The species is adapted to a range of tropical and subtropical environments and is recognized for its tolerance to drought and relatively poor soil conditions.
- Bael fruit is rich in dietary fibre and diverse phytochemicals, including phenolics, flavonoids, coumarins, terpenoids and alkaloids.
- Traditional medicinal applications are extensive, particularly for gastrointestinal disorders; however, much of the pharmacological evidence remains preclinical and requires clinical validation.
- India possesses substantial bael genetic diversity, with 278 accessions collected through a national exploration programme and a current major field collection of 338 accessions at ICAR-CIAH/CHES, Godhra.

- Conservation, characterization, molecular evaluation and utilization of bael germplasm are important for developing climate-resilient horticultural systems and value-added products.

Introduction

India is recognized as a centre of diversity for numerous fruit and medicinal plant species, including bael (*Aegle marmelos* (L.) Corrêa), a characteristic tree of the Indian subcontinent. Commonly known as bael, bel, Bengal quince or Indian quince, the species belongs to the family Rutaceae. It has long-standing cultural and medicinal associations in South Asia and is used in Ayurveda, Unani and diverse traditional healthcare practices. Reviews of its ethnomedicinal history indicate that different parts of the plant - including fruits, leaves, bark, roots and seeds - have been used traditionally for a range of ailments, particularly gastrointestinal disorders (Lyngdoh et al., 2019).

Bael is also an important underutilized fruit crop because of its ability to grow under relatively dry and stressful environmental conditions. It occurs

naturally and under cultivation across parts of the Indian subcontinent and extends into mainland and island Southeast Asia. Its tolerance of drought, adaptation to different soil conditions and ability to produce fruit under comparatively low-input conditions make it relevant to research on resilient horticultural systems.

The fruit has considerable food-processing potential. Ripe and unripe pulp can be utilized in beverages, preserves, marmalades, confectionery, dehydrated products and other processed foods. Its characteristic aroma, mucilaginous pulp and high fibre content further distinguish it from many commonly cultivated fruit crops. Reviews of bael fruit chemistry have identified phenolics, carotenoids, flavonoids, terpenoids, coumarins and alkaloids among its major groups of bioactive constituents.

Cytologically, *A. marmelos* is predominantly reported as a diploid species with $2n = 18$ chromosomes, although tetraploid plants with $2n = 36$ have also been documented in natural populations. A contemporary genome assembly of *A. marmelos* is approximately 276 Mb, while a complete chloroplast genome has been reported at 144,538 bp (Wang et al., 2023; Kaushik and Kumar, 2018). These genomic resources provide opportunities for future studies of genetic diversity, adaptation and crop improvement.

Taxonomic position

Rank	Classification
Kingdom	Plantae
Clade	Angiosperms
Clade	Eudicots
Order	Sapindales
Family	Rutaceae
Genus	<i>Aegle</i>
Species	<i>Aegle marmelos</i> (L.) Corrêa

The commonly used name “Citrus family” should be avoided in formal taxonomy; *Aegle* belongs to Rutaceae, the same family as *Citrus*, but is not itself a citrus genus.

Cultural, Ethnobotanical and Mythological Significance

Bael has a particularly prominent place in Hindu cultural traditions. The leaves, commonly called bilva or bel leaves, are traditionally offered to Lord Shiva and are associated with religious observances and temple practices. Traditional narratives found in Hindu religious literature associate the bilva tree with divine origins and with Shiva worship (Choudhary et al., 2021; Jadhav et al., 2025).

The characteristic trifoliate leaf is also interpreted symbolically in several religious traditions. Associations with Shiva's three eyes, the three *gunas* and other triadic concepts are elements of religious and cultural interpretation rather than botanical or pharmacological properties.

Origin and Distribution

Bael is native to the Indian subcontinent and occurs naturally in dry deciduous forests, woodland habitats and cultivated landscapes. Historical and botanical accounts indicate a distribution extending through India, Sri Lanka, Bangladesh, Pakistan and parts of mainland and island Southeast Asia (Venthodika et al., 2021).

Within India, bael is distributed widely, including in Uttar Pradesh, Bihar, Madhya Pradesh, Rajasthan, Gujarat, Haryana, Punjab, West Bengal, Odisha, Jharkhand, Chhattisgarh, Assam, Maharashtra, Karnataka, Andhra Pradesh and Tamil Nadu (Singh et al., 2019).

The species occurs across contrasting agro-climatic environments, although its performance depends on genotype, soil, moisture availability and management.

The Indian subcontinent represents an important centre of diversity and long-term cultivation of bael. Considerable morphological and biochemical variation has been documented among Indian populations and germplasm collections.

Botanical Description

Bael is a medium-sized, deciduous tree that may reach approximately 8–15 m under favourable conditions. The crown is generally irregular, and branches may bear spines (Baliga et al., 2011). Leaves are aromatic and commonly trifoliate, although variation occurs in leaf morphology (Choudhary et al., 2021).

The flowers are fragrant, bisexual and generally borne in axillary clusters or panicles. They are typically greenish-white to yellowish and contain numerous stamens. Floral morphology can vary among genotypes (Neeraj and Johar, 2017).

The fruit is globose to ovoid or pyriform, with a characteristic hard woody rind. At maturity, the pulp becomes soft, aromatic and orange to yellowish-orange. Numerous seeds are embedded in mucilage within distinct segments of the pulp. The combination of a hard shell and aromatic pulp is responsible for the characteristic appearance and traditional appeal of the fruit.

Bael exhibits substantial phenotypic variation in fruit size, shape, rind thickness, pulp characteristics, seed number and biochemical composition. Recent characterization studies

have demonstrated wide variation in fruit weight, pulp weight, yield and quality traits among germplasm maintained under rainfed conditions.

Cytogenetics, Pollination and Reproductive Biology

Bael is generally diploid with $2n = 18$ chromosomes, although tetraploid individuals with $2n = 36$ have also been reported. Cytological studies have shown normal meiosis and relatively high pollen fertility in both ploidy levels.

Bael is predominantly dependent on cross-pollination. Its fragrant flowers attract several insect visitors, and honeybees are important pollinators. Detailed reproductive studies have demonstrated that *A. marmelos* exhibits gametophytic self-incompatibility: pollen from the same genetic individual is substantially restricted in its growth through the style, whereas compatible cross-pollen can successfully progress towards fertilization (Baskin and Baskin, 2014).

This reproductive behaviour has important implications for fruit production and breeding. Although natural pollen transfer can be efficient, fruit and seed production may be reduced by post-pollination and post-fertilization processes. Therefore, the earlier description of bael as simply “predominantly cross-pollinated with some limited self-pollination” should be replaced with a more precise description emphasizing predominant out-crossing and self-incompatibility.

Seeds are relatively large, flattened and surrounded by mucilage. Earlier literature described rapid germination, generally within

approximately 2–3 weeks under favourable conditions. More recent seed research has demonstrated that bael seeds can retain viability under appropriate storage conditions, indicating that the previous statement that seeds necessarily require immediate sowing should be avoided (Vijay, 2025).

Climate Adaptation and Horticultural Potential

Bael is considered a hardy fruit tree with considerable adaptability to tropical and subtropical environments. Its natural distribution includes dry regions, and the species has demonstrated useful tolerance to drought and relatively marginal soil conditions. This adaptability has led to interest in its cultivation in arid and semi-arid environments.

Temperature tolerance varies with genotype, plant age, duration of exposure, moisture status and acclimation. Young trees may be more vulnerable to frost and extreme temperatures than established trees.

Bael can grow across a range of soil types and has been reported from both acidic and alkaline environments. Nevertheless, good drainage remains desirable for sustained growth and productivity. Its capacity to persist under water-limited conditions makes it a potentially useful component of diversified dryland horticulture, but drought tolerance should not be interpreted as complete immunity to water stress.

The current relevance of bael to climate-resilient horticulture lies in combining its inherent adaptation with appropriate genotypes, water-conserving practices, soil management, mulching, efficient irrigation where available and suitable planting material.

Fruit, Nutrition and Value Addition

Bael fruit is nutritionally and technologically important because of its pulp, fibre, characteristic aroma and phytochemical composition. Reported constituents include carbohydrates, dietary fibre, vitamins, minerals, carotenoids, phenolic compounds, flavonoids, terpenoids, coumarins and alkaloids (Baliga et al., 2011).

The fruit can be consumed fresh after ripening or processed into a range of products, including:

- beverages such as juice, squash, nectar, syrup and *sharbat*;
- preserves, marmalade and jelly;
- *murabba* and confectionery products;
- dehydrated pulp and powder;
- functional food formulations and blended beverages.

The hard rind provides some protection to the pulp and contributes to the fruit's relatively distinctive post-harvest characteristics. At the same time, the hard shell and relatively low level of organized commercial production can present challenges for mechanical processing and large-scale commercialization.

Recent germplasm evaluations indicate substantial variation in biochemical characteristics. A 2025 study of North Indian germplasm, for example, reported wide variation in fruit weight, yield, total soluble solids, sugars, acidity, vitamin C, carotenoids and tannins, demonstrating the potential for trait-specific selection and product-oriented breeding.

Phytochemical and Pharmacological Potential

Bael has attracted extensive phytochemical and pharmacological research. Different plant parts contain structurally diverse secondary metabolites, including coumarins, alkaloids, flavonoids, phenolic compounds, terpenoids and essential-oil constituents (Monika et al, 2023; Ahmad et al., 2021). Marmelosin and related coumarin compounds are among the better-known constituents investigated in *A. marmelos*.

Traditional medicine systems have used different parts of the plant for gastrointestinal and other health-related conditions. In particular, unripe fruit preparations have traditionally been used for diarrhoea and dysentery, while other plant parts have been incorporated into traditional formulations.

Experimental studies have reported antioxidant, antimicrobial, antidiarrhoeal, gastroprotective, anti-inflammatory, hepatoprotective, antidiabetic and other biological activities. However, the evidence base is heterogeneous and includes in vitro experiments, animal studies and traditional-use reports.

Bael and its constituents have demonstrated potentially relevant biological activities in preclinical studies, while evidence from well-controlled human clinical trials remains limited. Recent reviews similarly emphasize the need for additional clinical studies and safety evaluation before therapeutic claims can be established.

Bael Germplasm Resources and Conservation in India

Bael possesses considerable genetic and phenotypic diversity in India. Conservation of

this diversity is important because many traditional and wild trees have not been systematically characterized and may contain useful variation for fruit quality, yield, stress tolerance and biochemical traits.



Fig. 1: A. Bael fruit **B.** Bael Germplasm Conserved in the Field gene bank at Issapur Farm, ICAR-NBPGR, New Delhi

A national exploration and characterization programme supported through the National Medicinal Plants Board collected 278 bael accessions from several regions of India. The collection comprised 59 samples from Rajasthan and Gujarat, 95 from Uttar Pradesh and Bihar, 26 from Madhya Pradesh, 28 from Jharkhand, 37 from West Bengal, 17 from Odisha and 16 from Chhattisgarh. Elite germplasm was subsequently conserved at ICAR-CIAH, Bikaner; ICAR-CHES, Godhra; ICAR-CISH, Lucknow; and other collaborating locations.

Major conservation and research centres

ICAR-Central Institute for Arid Horticulture (CIAH), Bikaner

The institute has an important role in the conservation, characterization and utilization of arid and semi-arid fruit crops, including bael. It has contributed to the evaluation and development of bael planting material suitable for dryland environments (Tripathi et al., 2025).

ICAR - Central Horticultural Experiment Station (CHES), Godhra

The CHES, Godhra, functioning under ICAR-CIAH, hosts the National Active Germplasm Site for bael. A recent scientific study reports a collection comprising 217 clonal and 121 seedling accessions, totalling 338 accessions, making it the largest documented living bael germplasm collection currently reported from a single site.

The collection has supported characterization, evaluation and selection for fruit and quality traits and has contributed to the development of improved bael cultivars. Recent studies continue to demonstrate substantial genetic and phenotypic variation within this material (Singh et al., 2026).

ICAR-Central Institute for Subtropical Horticulture (CISH), Lucknow

ICAR-CISH has undertaken research on bael germplasm, breeding, characterization and production technologies and has contributed to the development and evaluation of improved material.

ICAR-National Bureau of Plant Genetic Resources (NBPGR), New Delhi

ICAR-NBPGR plays an important national role in plant genetic resource exploration, characterization, documentation and long-term conservation. Bael genetic resources collected through exploration programmes are part of the broader national plant genetic resource conservation framework.

Acharya Narendra Deva University of Agriculture and Technology

The university has contributed to the evaluation and development of bael material, including selections referred to as the Narendra Bael series.

Govind Ballabh Pant University of Agriculture and Technology

The university has contributed to bael evaluation and cultivar development, including selections such as Pant Aparna, Pant Shivani and Pant Sujata.

Table 1. Selected bael germplasm exploration and conservation information in India*

Region/state	Documented exploration
Uttar Pradesh + Bihar	95 accessions collected
Rajasthan + Gujarat	59 accessions collected
Madhya Pradesh	26 accessions collected
Jharkhand	28 accessions collected
West Bengal	37 accessions collected
Odisha	17 accessions collected
Chhattisgarh	16 accessions collected
Total national exploration	Collected 278 accessions

*Source: National Medicinal Plants Board, Government of India (2008).

Recent Advances in Bael Germplasm Characterization

Recent research has strengthened the case for systematic utilization of bael genetic diversity. A 2025 study of North Indian germplasm reported considerable variation in fruit length, circumference, fruit weight, shell thickness, seed number, yield and biochemical characteristics,

including soluble solids, sugars, acidity, vitamin C, carotenoids and tannins (Pandey et al., 2025).

Similarly, a 2026 study evaluating 69 bael genotypes under rainfed hot semi-arid conditions reported substantial variation in fruit weight, pulp weight, seed weight, fruit yield and quality traits (Singh et al., 2026). Such variation provides opportunities for selection of genotypes adapted to specific production environments and end uses (Pathirana et al., 2020).

These findings indicate that future bael improvement should move beyond selection based solely on fruit size. Breeding and germplasm evaluation should simultaneously consider:

- yield stability under water-limited conditions;
- fruit and pulp recovery;
- soluble solids and acidity;
- seed content and ease of processing;
- rind thickness;
- nutritional and phytochemical composition;
- tree architecture and precocity;
- disease and pest tolerance;
- reproductive compatibility;
- molecular genetic diversity.

Genomic Resources and Future Research

The emergence of genomic resources provides a new dimension to bael improvement. A contemporary *A. marmelos* genome assembly (*Aegle marmelos* cv. AEG genome v1.0) is approximately 276 Mb (Huang et al., 2024) while the complete chloroplast genome is 144,538 bp (Kaushik and Kumar, 2018; (Wang et al., 2023).

These resources can support phylogenetic studies, DNA-based identification, population genetics, marker development and future genome-assisted breeding. Molecular characterization is particularly important because bael populations show considerable morphological variation and because seed propagation can generate genetically variable progeny.

Future research should integrate field phenotyping with molecular markers, genomic data and biochemical profiling. Such an approach could help identify alleles or genomic regions associated with drought adaptation, fruit quality, pulp characteristics, yield and nutritionally important metabolites.

Conservation Priorities

Despite increasing scientific interest, several gaps remain in bael genetic resource conservation and utilization. First, field collections need systematic characterization using standardized descriptors and molecular markers. Second, duplication among collections should be assessed to improve the efficiency of ex situ conservation. Third, rare, geographically restricted and locally adapted populations require greater attention.

Both *ex situ* and *in situ* conservation are necessary. Field gene banks provide living material for characterization and breeding, whereas conservation in natural habitats and traditional landscapes helps maintain ecological and evolutionary diversity. At Issapur farm of ICAR-NBPGR, New Delhi, 17 accessions of bael germplasm are conserved in 'Field Genebank for Multipurpose Trees' of the semi-arid region conserving (ICAR-NBPGR, 2026; Fig. 1).

The development of a publicly accessible national database linking accession identity, geographic origin, passport information, phenotypic descriptors, molecular profiles and conservation status would substantially improve utilization of bael genetic resources.

Value Addition and Sustainable Horticulture

The future importance of bael extends beyond its role as a traditional medicinal plant. Its fruit can serve as a raw material for small-scale and industrial food processing, while the tree can contribute to diversified agroforestry and dryland horticultural systems.

The development of standardized processing technologies could improve pulp recovery, product consistency and marketability. Potential products include beverages, fruit bars, concentrates, powders, preserves and blended functional foods.

However, commercialization should be accompanied by scientific assessment of food safety, processing stability, nutrient retention and permissible health claims. Traditional use alone should not be interpreted as proof of therapeutic efficacy or safety at pharmacological doses.

Conclusion

Bael (*Aegle marmelos* (L.) Corrêa) is an important indigenous fruit tree combining cultural significance, nutritional value, phytochemical diversity and adaptation to challenging growing environments. Its long history of use in traditional medicine and its extensive distribution across South and Southeast Asia have contributed to its

recognition as a valuable underutilized fruit species.

Scientific research supports the presence of diverse bioactive compounds and demonstrates several biological activities in laboratory and preclinical studies. Nevertheless, the strength of evidence varies substantially among reported effects, and many therapeutic claims require confirmation through well-designed human clinical studies.

India possesses substantial bael genetic diversity. The national exploration programme documented 278 accessions, while the National Active Germplasm Site at ICAR-CHES, Godhra, currently maintains a reported 338 accessions comprising 217 clonal and 121 seedling accessions. Recent characterization studies demonstrate considerable variation in fruit, yield and biochemical traits, providing a foundation for trait-specific selection and crop improvement.

The future of bael research should therefore focus on integrated germplasm conservation, molecular characterization, climate-resilient genotype selection, reproductive biology, standardized phytochemical evaluation, food processing and scientifically rigorous assessment of health-related properties. Greater use of bael in sustainable horticulture and value-added food systems could contribute to diversification of fruit production, improved utilization of indigenous plant resources and enhanced resilience of farming systems in water-limited environments.

Bael may appropriately be described as a resilient and underutilized fruit crop with considerable nutritional, cultural and research potential. Its future significance will depend on

transforming this biological diversity and traditional knowledge into scientifically validated, conservation-oriented and economically viable horticultural systems.

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