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Morphological characterization of bael (*Aegle marmelos* Correa.) accession based on leaf traits from Central India (Chhattisgarh and Madhya Pradesh)

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ABSTRACT

Bael (*Aegle marmelos* Correa.) is an underutilized fruit tree possessing considerable variability among seedling-origin populations, making systematic characterization important for germplasm conservation and utilization. The present study was conducted during 2023–24 and 2024–25 to characterize qualitative leaf traits of 64 seedling-origin bael accessions collected from different locations of Chhattisgarh (33) and Madhya Pradesh (31), Central India. Leaf characterization was carried out using PPV&FRA DUS guidelines and the NBPGR bael descriptor. Variation was assessed for leaf colour, overall leaf shape, central leaflet shape, leaf apex, leaf base, leaf surface, leaf margin and leaf size. Considerable morphological variation was observed among the accessions. Dark green leaves were predominant (46.88%), followed by green (40.63%) and light green (12.50%). Lanceolate-to-ovate leaf shape was most frequent (40.63%), while ovate central leaflets accounted for 53.13% of the accessions. Aristate apex (46.88%) and round leaf base (42.19%) were the predominant character states. Rough leaf surface (78.13%) and crenate leaf margin (70.31%) were also predominant, whereas small leaves constituted the largest leaf-size class (45.31%). Differences in the frequency of several character states were observed between Chhattisgarh and Madhya Pradesh, particularly for leaf shape, central leaflet shape, leaf base and leaf margin. The observed variation demonstrates considerable morphological diversity in the evaluated bael germplasm and provides useful baseline information for accession characterization, conservation and further evaluation of bael genetic resources in Central India. Since the study was based on field-grown seedling-origin accessions, the observed variation represents phenotypic expression and should not be interpreted as genetic variation alone without further common-environment or molecular validation.

Keywords: *Aegle marmelos*, Bael germplasm, Leaf morphology, Qualitative traits, Central India

Introduction

Bael (*Aegle marmelos* Correa.) is an important underutilized fruit tree belonging to the family Rutaceae. It is commonly known as Bengal quince, Bilva, Bilpatre, Maredu and several other vernacular names. The species is subtropical, deciduous and highly hardy in nature, with the ability to withstand relatively adverse environmental conditions. Bael can grow up to an altitude of about 1200 m above mean sea level and possesses a chromosome number of $2n = 36$. The tree generally attains a height of 6–8 m and bears trifoliate, aromatic leaves. The terminal leaflet may reach about 5.7 cm in length and 2.8 cm in breadth, whereas the lateral leaflets are approximately 4.1 cm long and 2.2 cm wide (Allen, 1969; Nair *et al.*, 2016) [1, 2]. Bael is considered native to India, with its origin associated with the Eastern Ghats and Central India. It is distributed widely throughout the country and is also cultivated or found naturally in several South and South-East Asian countries. Within India, its distribution is particularly prominent in the eastern Gangetic plains and adjoining regions, including Uttar Pradesh, Bihar, Madhya Pradesh, Chhattisgarh, Jharkhand and Odisha. Natural populations have also been reported from forest areas, where considerable diversity occurs. The ability of bael to survive under comparatively harsh and water-deficit conditions makes it particularly relevant for marginal and rainfed environments.

Bael possesses considerable cultural, nutritional, medicinal and economic importance. The tree has been associated with Indian religious and cultural traditions since ancient times, while its leaves and fruits are used in religious offerings. Apart from its cultural significance, almost every part of the plant has been utilized traditionally. The ripe fruit pulp is consumed fresh and is also processed into sharbat, jam, murabba, squash, powder, pickle, nectar, toffee, slab and other value-added products. Different plant parts have also been used in traditional Ayurvedic preparations. The fruit contains several bioactive constituents, including alkaloids, coumarins and steroids. Marmelosin has been reported as an important bioactive constituent of bael fruit, with the concentration reported in the range of 0.03–0.37%, depending upon variety and locality (Dixit *et al.*, 1932) [3].

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From the nutritional standpoint, bael fruit is an important source of carbohydrates, vitamins and other nutrients. Per 100 g of edible portion, bael fruit contains approximately 61.5 g moisture, 1.8 g protein, 0.39 g fat, 31.8 g carbohydrate and 1.7 g minerals. It also contains about 55 mg carotene, 0.13 mg thiamine, 1.19 mg riboflavin, 1.1 mg niacin and 8.0 mg vitamin C (Gopalan *et al.*, 1985) [4]. The relatively high riboflavin content further contributes to its nutritional importance. In addition, bael seeds have been reported to contain approximately 62% protein, while seed oil constitutes about 34.4% on a dry-weight basis. The reported fatty-acid composition of seed oil includes approximately 16.6% palmitic acid, 8.8% stearic acid, 30.5% oleic acid, 30.0% linoleic acid and 8.1% linolenic acid.

Although bael has a wide geographical distribution, its organized commercial cultivation remains comparatively limited. According to the bael literature available in the present thesis sources, India had approximately 8.43 thousand hectares under bael cultivation with an annual production of 81.88 thousand tonnes. Odisha accounted for about 7.28 thousand hectares and 45.29 thousand tonnes of production. In Chhattisgarh, bael was reported over approximately 0.06 thousand hectares, producing about 0.43 thousand tonnes, while Mahasamund district accounted for approximately 0.04 thousand hectares and 0.33 thousand tonnes of production (Anonymous, 2021a,b) [5]. These figures indicate that, despite its adaptability and multipurpose value, bael remains relatively less exploited as a systematically managed fruit crop.

A major feature of bael is the considerable variability observed among seedling and wild populations. Variation has been documented in tree growth, leaf morphology, fruit size, fruit shape, pulp content, seed characteristics, physicochemical properties, biochemical constituents and yield. Such variability is of particular importance because bael is largely propagated through seed, resulting in considerable heterogeneity among naturally occurring and seedling-derived plants. Morphological characterization is therefore an important first step in identifying and conserving valuable germplasm.

Considerable variation has been recorded for important fruit characters. Nath *et al.* (2003) [6], while evaluating bael diversity in East Central India, reported fruit weight ranging from 0.50 to 2.60 kg and fruit length from 16.80 to 30.50 cm, while skull thickness varied from 0.17 to 0.40 cm. Srivastava *et al.* (2004) [7] reported fruit weight ranging from 0.997 to 3.618 kg among bael cultivars, with fruit length varying from 14.00 to 19.50 cm and breadth from 13.60 to 21.25 cm. Such wide ranges clearly demonstrate the extent of phenotypic variation available within the crop.

More detailed characterization by Dhakar *et al.* (2019) [8] involving 75 bael genotypes further demonstrated substantial variability in fruit characters. Fruit weight ranged from 315.20 to 1608.65 g, fruit length from 81.39 to 173.43 mm, fruit width from 89.76 to 136.35 mm, skin weight from 88.62 to 358.07 g, number of seeds from 37.67 to 195.40, seed weight from 7.48 to 54.33 g, and pulp weight from 201.17 to 1243.87 g. Skin percentage varied from 9.59 to 42.83%, seed percentage from 0.97 to 7.97%, pulp percentage from 53.72 to 89.33%, skin thickness from 1.43 to 4.10 mm, and fruit volume from 285 to 1555 cc.

Such variability is highly valuable for bael improvement because desirable fruit ideotypes require combinations of characters such as higher fruit weight, greater pulp percentage, lower seed content, suitable fruit size, thinner shell, desirable soluble solids and good sensory quality. Genetic-divergence studies have also indicated that characters such as fruit weight, fruit length, seed number and weight, fibre content, ascorbic acid and petiole length contribute substantially to divergence among bael genotypes. Therefore, systematic characterization of available germplasm can facilitate the identification of promising genotypes and provide useful material for future selection and breeding programmes.

The genetic resources of bael are particularly important in Central India, including Madhya Pradesh and Chhattisgarh, where wild, natural and seedling populations occur in forest, tribal and comparatively dry regions. The occurrence of such populations provides an opportu-

nity to explore locally adapted genetic resources that may possess desirable characteristics related to plant adaptability, fruit quality, yield and nutritional attributes. However, a substantial proportion of the available diversity remains insufficiently characterized and utilized. Hence, systematic exploration, collection, characterization and evaluation of bael genotypes are necessary for effective conservation and utilization of this genetic wealth.

Despite the considerable variability reported for individual traits, integrated evaluation of bael genotypes combining tree, leaf and floral morphology with fruit physicochemical, biochemical, yield and sensory attributes remains important, particularly for germplasm available in Central India. Characterization of such variability can help in identifying superior and distinct genotypes, conserving valuable genetic resources and establishing a scientific basis for future selection and breeding programmes. Therefore, the present investigation entitled “Studies on Genetic Variability in Bael (*Aegle marmelos* Correa) Available in Central – India” was undertaken to assess the extent of genetic variability among available bael genotypes and to identify promising genotypes based on morphological, physicochemical, biochemical, yield and sensory attributes.

2. Materials and Methods

2.1 Experimental site and location

The study was conducted during 2023–24 and 2024–25 in selected areas of Central India to assess morphological variation among bael (*Aegle marmelos* Correa) genotypes. The field survey was carried out in two states, Chhattisgarh and Madhya Pradesh. In Chhattisgarh, the survey covered Raigarh, Sarangarh-Bilaigarh, Sakti and Bilaspur districts, whereas in Madhya Pradesh, genotypes were collected from Jabalpur, Rewa, Satna, Panna and Maihar districts. These locations represented variation in geographical position and elevation. Chhattisgarh lies approximately between 17°46' and 24°05' N latitude and 80°15' and 84°24' E longitude. The surveyed locations included Sakti (22.024° N, 82.960° E; 294.4 m above mean sea level), Sarangarh-Bilaigarh (21.54° N, 83.13° E; approximately 223 m), Raigarh (approximately 21°20'–22°47' N and 82°57'–83°47' E; approximately 244 m) and Bilaspur (approximately 21.47°–23.80° N and 81.14°–83.15° E; approximately 244 m). The surveyed region of Madhya Pradesh extended approximately between 21°17' and 26°52' N latitude and 74°08' and 82°49' E longitude. The collection sites included Jabalpur (23.17° N, 79.95° E; approximately 411 m), Rewa (24.32° N, 81.15° E; approximately 316 m), Satna (24.58° N, 80.83° E; approximately 317 m), Panna (24.72° N, 80.19° E; approximately 427 m) and Maihar (24.27° N, 80.75° E; approximately 367 m above mean sea level).

2.2 Selection of experimental material

Bael trees were identified and selected through field observations and inspection of information obtained through consultations with local farmers, villagers and agricultural officials. Preference was given to seedling-origin trees showing apparent phenotypic differences in tree and fruit characteristics. A total of 64 healthy bael genotypes, approximately 20–30 years old, were selected for characterization based on their initial visual heterogeneity. The selected genotypes represented two geographical groups: 33 genotypes from Chhattisgarh and 31 genotypes from Madhya Pradesh. Because the seedling trees did not have standardized varietal names, accession codes were assigned as CGB 1–CGB 33 for the Chhattisgarh group and MPB 1–MPB 31 for the Madhya Pradesh group.

2.3 Leaf sampling and characterization

Leaf observations were recorded as part of the morphological characterization of the selected bael genotypes. The characterization followed the Guidelines for the Conduct of Test for Distinctiveness, Uniformity and Stability (DUS) of bael under the Protection of Plant Varieties and Farmers' Rights Authority (PPV&FRA), Government of India, together with the bael descriptor developed by the National Bureau of Plant Genetic Resources (NBPGR), New Delhi. Fully de-

veloped and healthy leaves were used for characterization. Leaf traits were evaluated primarily through visual observation, while leaf surface texture was assessed through visual and tactile examination. For leaf-margin characterization, ten leaves from each genotype were examined to account for variation among leaves within a genotype. The leaf traits were grouped into qualitative/categorical parameters and included leaf colour, leaf shape, central leaflet shape, lateral leaflet shape, leaf apex, leaf base, leaf surface, leaf margin and leaf size.

2.3.1 Leaf colour

Variation in leaf colour was assessed visually using a horticultural colour chart on fully developed leaves. Based on the observed colour differences, the genotypes were classified into three categories:

- **Light green** – score 3
- **Green** – score 5
- **Dark green** – score 7

The colour category representing the predominant condition of the leaves was recorded for each genotype.

2.3.2 Leaf shape

Overall leaf shape was assessed by visual observation of fully developed leaves. The shape of leaves from each genotype was compared with the standard morphological patterns illustrated for bael, and the genotype was assigned to the corresponding category according to the observed leaf form.

2.3.2.1 Central leaflet shape

The shape of the central leaflet was assessed visually using fully developed leaves. The predominant form observed in each genotype was recorded and classified into the following categories:

- **Broadly ovate-lanceolate to ovate** – score 1
- **Lanceolate** – score 3
- **Ovate to elliptic** – score 5

2.3.2.2 Lateral leaflet shape

Variation in lateral leaflet morphology was assessed visually on fully developed leaves. The predominant lateral leaflet shape observed in each genotype was classified as:

- **Ovate** – score 1
- **Elliptical** – score 3
- **Lanceolate** – score 5

2.3.3 Leaf apex

Leaf apex characteristics were determined through visual observation. The predominant apex form for each genotype was recorded and classified into:

- **Acuminate** – score 3
- **Acute** – score 7
- **Aristate** – score 9

2.3.4 Leaf base

The shape of the leaf base was assessed visually using fully developed leaves. Based on the predominant morphology, leaf bases were classified as:

- **Cuneate** – score 1
- **Round** – score 3
- **Attenuate** – score 5
- **Tapering** – score 7

2.3.5 Leaf surface

Leaf surface texture was assessed through visual and tactile examination of fully developed leaves. Based on surface characteristics, the genotypes were classified into two categories:

- **Smooth** – score 1
- **Rough** – score 9

2.3.6 Leaf margin

Variation in leaf margin was assessed visually using ten fully developed leaves per genotype. The margin type observed in the leaves was compared with the standard morphological patterns, and each genotype was categorized according to the predominant margin type:

- **Crenulate** – score 3
- **Crenate** – score 7

2.3.7 Leaf size

Leaf size was assessed visually based on the variation observed among the genotypes. The genotypes were classified into three categories:

- **Small** – score 3
- **Medium** – score 5
- **Tall** – score 7

2.4 Recording of leaf characters

For each genotype, the predominant character state was recorded for the respective qualitative leaf traits. Descriptor scores were assigned according to the predefined categories described above. The resulting observations were compiled genotype-wise to assess the extent of morphological variation in leaf characteristics among the 64 bael genotypes. The observations generated from leaf colour, overall leaf shape, central and lateral leaflet shape, apex, base, surface, margin and leaf size were subsequently used for comparative characterization of the genotypes and, where applicable, multivariate analysis of phenotypic variation.

3. Results

3.1 Variability in qualitative leaf traits

Considerable phenotypic variation was observed among the 64 bael accessions for the qualitative leaf traits evaluated. The accessions differed in leaf colour, overall leaf shape, central leaflet morphology, leaf apex, leaf base, surface texture, margin characteristics and leaf size. The frequency distribution of the observed character states demonstrated substantial morphological heterogeneity within the evaluated bael germplasm.

Table 1. Frequency distribution of qualitative leaf characters among bael accessions from Chhattisgarh and Madhya Pradesh

Leaf trait	Character state	Overall (<i>n</i> = 64) No.	Overall (%)	Chhattisgarh (<i>n</i> = 33) No.	Chhattisgarh (%)	Madhya Pradesh (<i>n</i> = 31) No.	Madhya Pradesh (%)
Leaf colour	Light green	8	12.5	5	15.15	3	9.68
	Green	26	40.63	15	45.45	11	35.48
	Dark green	30	46.88	13	39.39	17	54.84

(continued on next page)

Leaf trait	Character state	Overall (n = 64) No.	Overall (%)	Chhattisgarh (n = 33) No.	Chhattisgarh (%)	Madhya Pradesh (n = 31) No.	Madhya Pradesh (%)
Leaf shape	Lanceolate to ovate	26	40.63	13	39.39	13	41.94
	Lanceolate	17	26.56	11	33.33	6	19.35
	Broadly ovate	12	18.75	3	9.09	9	29.03
	Ovate	9	14.06	6	18.18	3	9.68
Central leaflet shape	Ovate	34	53.13	15	45.45	19	61.29
Leaf apex	Lanceolate	30	46.88	18	54.55	12	38.71
	Acuminate	19	29.69	7	21.21	12	38.71
	Acute	15	23.44	10	30.3	5	16.13
	Aristate	30	46.88	16	48.48	14	45.16
Leaf base	Cuneate	24	37.5	16	48.48	8	25.81
	Round	27	42.19	10	30.3	17	54.84
	Attenuate	10	15.63	6	18.18	4	12.9
	Tapering	3	4.69	1	3.03	2	6.45
Leaf surface	Smooth	14	21.88	7	21.21	7	22.58
	Rough	50	78.13	26	78.79	24	77.42
Leaf margin	Crenulate	19	29.69	7	21.21	12	38.71
	Crenate	45	70.31	26	78.79	19	61.29
Leaf size	Small	29	45.31	15	45.45	14	45.16
	Medium	21	32.81	11	33.33	10	32.26
	Large	14	21.88	7	21.21	7	22.58

3.1.1 Leaf colour

Three distinct leaf-colour classes, namely light green, green and dark green, were recorded among the accessions. Dark green foliage was the predominant character state, occurring in 30 of the 64 accessions (46.88%), followed by green foliage in 26 accessions (40.63%). Light green leaves were comparatively less frequent and were observed in 8 accessions (12.50%). The distribution also differed between the two geographical groups. Among the 33 Chhattisgarh accessions, green leaves were recorded in 15 accessions (45.45%), dark green in 13 (39.39%), and light green in 5 (15.15%). In contrast, among the 31 Madhya Pradesh accessions, dark green was predominant, occurring in 17 accessions (54.84%), followed by green in 11 (35.48%) and light green in 3 (9.68%). Thus, although all three colour classes occurred in both geographical groups, dark green foliage was particularly frequent among the Madhya Pradesh accessions.

3.1.2 Leaf shape

Marked variation was observed in the overall shape of leaves. After standardizing capitalization and treating "Lanceolate to Ovate" and "Lanceolate to ovate" as the same morphological class, lanceolate to ovate was the most frequent leaf form, occurring in 26 accessions (40.63%). This was followed by lanceolate leaves in 17 accessions (26.56%), broadly ovate leaves in 12 accessions (18.75%), and ovate leaves in 9 accessions (14.06%). In the Chhattisgarh group, lanceolate leaves were relatively frequent (11 accessions; 33.33%), followed by lanceolate-to-ovate (13; 39.39%), ovate (6; 18.18%) and broadly ovate (3; 9.09%). In Madhya Pradesh, lanceolate-to-ovate leaves were predominant (13 accessions; 41.94%), followed by broadly ovate (9; 29.03%), lanceolate (6; 19.35%) and ovate (3; 9.68%). These observations indicate appreciable variation in leaf architecture between and within the two collection groups.

3.1.3 Central leaflet shape

Variation in central leaflet morphology was also evident among the accessions. Two predominant forms were represented in the tabulated observations: ovate and lanceolate. Ovate central leaflets were recorded in 34 accessions (53.13%), whereas lanceolate central leaflets occurred in 30 accessions (46.88%). A difference was apparent between the geographical groups. In Chhattisgarh, lanceolate central leaflets were more frequent, occurring in 18 of 33 accessions

(54.55%), compared with 15 accessions (45.45%) having ovate leaflets. Conversely, in Madhya Pradesh, ovate central leaflets predominated, occurring in 19 accessions (61.29%), while lanceolate leaflets were recorded in 12 accessions (38.71%). This contrasting distribution indicates substantial diversity in leaflet morphology within the studied material.

3.1.4 Leaf apex

Three distinct apex types—aristate, acuminate and acute—were observed across the 64 accessions. The aristate apex was the most prevalent, occurring in 30 accessions (46.88%), followed by acuminate in 19 accessions (29.69%) and acute in 15 accessions (23.44%). Among Chhattisgarh accessions, aristate apex was recorded in 16 accessions (48.48%), acute in 10 (30.30%), and acuminate in 7 (21.21%). In Madhya Pradesh, aristate apex occurred in 14 accessions (45.16%), acuminate in 12 (38.71%), and acute in 5 (16.13%). Thus, aristate apex represented the predominant character state in both geographical groups, although acuminate apex occurred relatively more frequently in the Madhya Pradesh group.

3.1.5 Leaf base

Four types of leaf base cuneate, round, attenuate and tapering—were identified. Round leaf base was the most common, occurring in 27 accessions (42.19%), closely followed by cuneate in 24 accessions (37.50%). Attenuate leaf bases were observed in 10 accessions (15.63%), whereas tapering bases were least frequent, being recorded in only 3 accessions (4.69%). The geographical groups showed a noticeable difference in distribution. In Chhattisgarh, cuneate was the predominant base type (16 accessions; 48.48%), followed by round (10; 30.30%), attenuate (6; 18.18%) and tapering (1; 3.03%). In Madhya Pradesh, round leaf base predominated (17 accessions; 54.84%), followed by cuneate (8; 25.81%), attenuate (4; 12.90%) and tapering (2; 6.45%).

3.1.6 Leaf surface

Leaf surface texture showed a pronounced predominance of the rough type. Rough leaf surfaces were recorded in 50 accessions (78.13%), whereas smooth surfaces were observed in 14 accessions (21.88%). Within the Chhattisgarh group, rough leaf surfaces occurred in 26 accessions (78.79%) and smooth surfaces in 7 (21.21%). A similar dis

tribution was observed in Madhya Pradesh, where rough surfaces were recorded in 24 accessions (77.42%) and smooth surfaces in 7 (22.58%). The close proportions between the two geographical groups indicate that rough leaf surface was consistently predominant across the studied material.

3.1.7 Leaf margin

Two distinct leaf-margin types, crenate and crenulate, were recorded. The crenate margin was predominant, being observed in 45 accessions (70.31%), whereas crenulate margins occurred in 19 accessions (29.69%). In Chhattisgarh, crenate margin was recorded in 26 accessions (78.79%), while crenulate margin occurred in 7 accessions (21.21%). Similarly, in Madhya Pradesh, 19 accessions (61.29%) exhibited crenate margins and 12 accessions (38.71%) exhibited crenulate margins. Therefore, crenate margin was the dominant character state in both groups, although crenulate margins were relatively more frequent in the Madhya Pradesh collection.

3.1.8 Leaf size

Considerable variation was also recorded for leaf size, with three classes represented in the dataset: small, medium and large. Small-sized leaves were most frequent, occurring in 29 accessions (45.31%), followed by medium-sized leaves in 21 accessions (32.81%) and large-sized leaves in 14 accessions (21.88%). The Chhattisgarh group showed 15 small (45.45%), 11 medium (33.33%), and 7 large (21.21%) leaf types. Similarly, the Madhya Pradesh group contained 14 small (45.16%), 10 medium (32.26%), and 7 large (22.58%) leaf types. The remarkably similar distribution of leaf-size classes between the two groups suggests that all three size categories were represented across the geographical collections.

Discussion

4.1 Variability in qualitative leaf traits

Considerable variation was observed among the 64 bael accessions for leaf colour, shape, central leaflet, apex, base, surface, margin and size, indicating substantial phenotypic diversity in the seedling-origin material collected from Central India. Similar diversity in vegetative and leaf characters has been reported in bael by Singh *et al.* (2015) [9], Singh *et al.* (2024) [10] and Singh *et al.* (2025) [11]. Such variation may arise from genetic differences among seedling-derived trees, while environmental factors can also modify the expression of leaf traits. Therefore, the present variation represents phenotypic diversity and cannot be considered exclusively genetic without common-environment or molecular confirmation. The genetic and environmental regulation of leaf morphology has also been demonstrated in other plant systems (Tsukaya, 2006; Nicotra *et al.*, 2011; Bhatia *et al.*, 2021) [12, 13, 14].

4.1.1 Leaf colour

Dark green leaves were predominant (46.88%), followed by green (40.63%) and light green (12.50%). Similar light, green and dark-green colour classes have been documented in bael by Singh *et al.* (2015) [9] and Singh *et al.* (2024) [10]. The higher proportion of dark-green leaves in Madhya Pradesh (54.84%) than Chhattisgarh (39.39%) may reflect differences in genotype composition as well as site conditions. Since leaf colour can be influenced by chlorophyll status, light, temperature, water and nutrition, the observed differences should be interpreted as phenotypic rather than purely genetic variation (Nicotra *et al.*, 2011; Reich, 2014) [13].

4.1.2 Leaf shape

Lanceolate-to-ovate leaves were most frequent (40.63%), followed by lanceolate (26.56%), broadly ovate (18.75%) and ovate (14.06%). The occurrence of several leaf-shape types agrees with the substantial morphological variation reported in bael by Singh *et al.* (2015) [9], Singh *et al.* (2018) [15] and Singh *et al.* (2024) [10]. Broadly ovate leaves were more frequent in Madhya Pradesh (29.03%) than

Chhattisgarh (9.09%), whereas lanceolate leaves were more common in Chhattisgarh (33.33%) than Madhya Pradesh (19.35%). Such differences may reflect variation in the composition of seedling populations, although environmental plasticity cannot be excluded. Leaf shape is controlled by developmental processes involving cell division and expansion and can also respond to environmental conditions (Tsukaya, 2006; Bhatia *et al.*, 2021) [12, 14].

4.1.3 Central leaflet shape

Ovate central leaflets predominated (53.13%), while lanceolate leaflets represented 46.88 per cent of accessions. Similar variation in leaflet morphology has been reported in bael by Singh *et al.* (2015) [9] and Singh *et al.* (2024) [10]. Ovate central leaflets were more frequent in Madhya Pradesh (61.29%), whereas lanceolate leaflets predominated in Chhattisgarh (54.55%). These differences may indicate variation in the morphological composition of the two regional populations, but environmental effects on leaf development should also be considered. Thus, central leaflet shape is useful as a descriptor, particularly when combined with other leaf characters.

4.1.4 Leaf apex

Aristate apex was predominant (46.88%), followed by acuminate (29.69%) and acute (23.44%). Comparable variation in apex type has been reported among bael varieties by Singh *et al.* (2015) [9], Singh *et al.* (2018) [15] and Singh *et al.* (2024) [10]. Aristate leaves occurred at similar frequencies in Chhattisgarh (48.48%) and Madhya Pradesh (45.16%), whereas acuminate and acute forms differed between regions. Such variation may result from differences in developmental patterns governing leaf-tip formation, with both genotype and environment potentially influencing final morphology (Byrne *et al.*, 2001; Tsukaya, 2006) [16, 12].

4.1.5 Leaf base

Four leaf-base types were recorded, with round (42.19%) and cuneate (37.50%) being predominant, followed by attenuate (15.63%) and tapering (4.69%). Similar variation in leaf base has been reported in bael by Singh *et al.* (2015) [9], Singh *et al.* (2024) [10] and Singh *et al.* (2025) [11]. Cuneate bases predominated in Chhattisgarh (48.48%), whereas round bases were dominant in Madhya Pradesh (54.84%). The contrasting regional frequencies suggest differences in population composition, although field environmental effects cannot be separated from genetic effects in the present study. Leaf base, particularly when considered with apex and margin, therefore provides a useful component of the morphological identity of bael accessions.

4.1.6 Leaf surface

Rough leaves predominated (78.13%), while smooth leaves represented 21.88 per cent of accessions. A similar occurrence of smooth and rough leaf surfaces was reported in bael by Singh *et al.* (2015) [9] and Singh *et al.* (2024) [10]. The nearly identical frequency of rough leaves in Chhattisgarh (78.79%) and Madhya Pradesh (77.42%) suggests relatively consistent expression of this character across the two collections. Nevertheless, visual surface classification alone cannot establish the anatomical or genetic basis of the difference; therefore, it is best treated as a qualitative descriptor.

4.1.7 Leaf margin

Crenate margin was predominant (70.31%), while crenulate margin occurred in 29.69 per cent of accessions. Variation between crenate and crenulate margins has also been reported in bael by Singh *et al.* (2015) [9], Singh *et al.* (2018) [15] and Singh *et al.* (2024) [10]. Crenate margins were more frequent in Chhattisgarh (78.79%) than Madhya Pradesh (61.29%). Leaf-margin morphology is developmentally regulated and can differ among genotypes because of differences in marginal growth processes; auxin-mediated developmental mechanisms have also been associated with leaf-margin formation (Kawamura *et al.*, 2010) [17]. Thus, leaf margin provides a useful supplementary character for accession identification.

4.1.8 Leaf size

Small leaves were predominant (45.31%), followed by medium (32.81%) and large leaves (21.88%). Variation in leaf dimensions among bael genotypes has been documented by Singh *et al.* (2015) [9] and Singh *et al.* (2024) [10]. The frequencies were remarkably similar between Chhattisgarh and Madhya Pradesh, indicating relatively consistent representation of the three size classes. However, leaf size is influenced by both genotype and environmental conditions such as light, temperature and water availability; therefore, the observed differences should not be interpreted as genetic variation alone (Nicotra *et al.*, 2011; Bhatia *et al.*, 2021) [13, 14].

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Declarations

Conflict of interest: The authors declare that they have no conflict of interest.
Data availability: The data supporting the findings of this study are available from the corresponding author upon reasonable request.
Consent to Publish declaration: not applicable.
Ethics declaration: not applicable.

Frequency distribution of qualitative leaf traits among 64 bael accessions							
Leaf trait	Character state	Overall (n = 64) No.	Overall (%)	Chhattisgarh (n = 33) No.	Chhattisgarh (%)	Madhya Pradesh (n = 31) No.	Madhya Pradesh (%)
Leaf colour	Light green	8	12.50	5	15.15	3	9.68
	Green	26	40.63	15	45.45	11	35.48
	Dark green	30	46.88	13	39.39	17	54.84
Leaf shape	Lanceolate to ovate	26	40.63	13	39.39	13	41.94
	Lanceolate	17	26.56	11	33.33	6	19.35
	Broadly ovate	12	18.75	3	9.09	9	29.03
	Ovate	9	14.06	6	18.18	3	9.68
Central leaflet shape	Ovate	34	53.13	15	45.45	19	61.29
	Lanceolate	30	46.88	18	54.55	12	38.71
Leaf apex	Acuminate	19	29.69	7	21.21	12	38.71
	Acute	15	23.44	10	30.30	5	16.13
	Aristate	30	46.88	16	48.48	14	45.16
Leaf base	Cuneate	24	37.50	16	48.48	8	25.81
	Round	27	42.19	10	30.30	17	54.84
	Attenuate	10	15.63	6	18.18	4	12.90
	Tapering	3	4.69	1	3.03	2	6.45
Leaf surface	Smooth	14	21.88	7	21.21	7	22.58
	Rough	50	78.13	26	78.79	24	77.42
Leaf margin	Crenulate	19	29.69	7	21.21	12	38.71
	Crenate	45	70.31	26	78.79	19	61.29
Leaf size	Small	29	45.31	15	45.45	14	45.16
	Medium	21	32.81	11	33.33	10	32.26
	Large	14	21.88	7	21.21	7	22.58

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