Plant Archives Vol. 26, Supplement 2, 2026 pp.3523-3532 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org
DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2026.v26.supplement-2.448

DIVERSITY ASSESSMENT OF MORPHOLOGICAL, BIOCHEMICAL, AND BIOACTIVE TRAITS IN BAEL (*Aegle marmelos* L.) UNDER SEMI-ARID LATERITIC CONDITIONS

Pradipto Kumar Mukherjee, Payel Das, Urmila Tudu, Gautam Mandal and Prahlad Deb*
Department of Horticulture and Postharvest Technology Institute of Agriculture,
Visva-Bharati, Sriniketan-731236, West Bengal, India
*Corresponding author E-mail: debprld@yahoo.com
(Date of Receiving : 13-05-2026; Date of Revision : 15-07-2026; Date of Acceptance : 31-07-2026)

ABSTRACT

Bael (*Aegle marmelos* L.) is an underutilized fruit of the Rutaceae family widely valued for its nutritional richness, medicinal properties and cultural significance in India. The present study was conducted to evaluate the diversity of Bael accessions collected from semi-arid lateritic belt of West Bengal based on morpho-biochemical parameters. Fifteen Bael accessions were collected and characterized based on twenty- three different morphological, biochemical and bioactive compound characters. The fruit morphological parameters showed significant variation which ranged from 206.4−972.24 gm for weight, 72.81−125.65 mm for length, 72.17−112.96 mm for diameter, and 115.25−950.45 ml for volume. The accession BA-10 demonstrated the maximum TSS (36.8 ºBrix), total sugar (23.12%) and reducing sugar content, indicating a very sweet profile. The β-carotene content ranged from 122.5 to 238.4 μg/100g, with BA-15 recording the maximum value. Correlation analysis revealed a strong positive correlation between fruit weight, fruit volume, fruit length, fruit diameter, pulp weight, edible portion, fibre content and shell weight. However, this study observed a strong negative correlation between fruit weight, total sugar % and antioxidant % indicating large size fruit to be less sweet with lesser antioxidant potential. Cluster analysis revealed separated fifteen accessions into two cluster with cluster I having 1 accession and cluster II having 14 accessions further divided into sub-clusters. The accession BA-1 grouped distinctly into cluster I indicating its genetic distinctness. Thus, in the semi-arid lateritic belt of West Bengal, Bael exhibits significant genetic diversity which can act as potential sources in varietal breeding programmes.
***Keywords* :** Bael, diversity, correlation, biochemical, antioxidant.

Introduction

Bael [*Aegle marmelos* L.) also known as Bengal quince, stone apple, golden apple or wood apple is an important minor arid fruit crop belonging to the family Rutaceae. It is an underutilized species indigenous to India and is widely recognized for its medicinal, therapeutic, and religious significance (Baliga *et al*., 2011; Bharadwaj *et al*., 2015; Katram *et al*., 2021; Pathirana *et al*., 2020a; Rahman & Parvin, 2014). The bael tree is deciduous and can attain a height of up to 10 m, characterized by numerous spiny branches and alternate leaves (Dhankar *et al*., 2011; Hazarika *et al*., 2020; Orwa *et al*., 2009). The flowers are bisexual, greenish-white, and emit a sweet fragrance (Sharma *et al*., 2007). The fruits are round to oval with a hard, woody shell, and the yellow pulp is sweet, aromatic, and mucilaginous, containing numerous seeds (Sarkar *et al*., 2020). The pulp has diverse culinary applications, including preparation of juices, squashes, and desserts such as puddings, jellies, and cakes (Banerjee *et al*., 2024; Sonawane *et al*., 2020).

Nutritionally, Bael is a rich source of vitamins like B (especially riboflavin), A and C. Also, numerous bioactive compounds like coumarins, marmelosin, scoparone, scopoletin, marmelide, aegeline, umbelliferone, and marmesin (Banerjee *et al*., 2024;

Pathirana *et al*., 2020a; Sharma *et al*., 2022). Bael is one of the most useful medicinal trees in India and every part of the plant is utilized in making traditional formulations (Sharma *et al*., 2007; Pandey *et al*., 2025). The leaves of bael tree are used to treat jaundice and other gastrointestinal ailments (Sanghi and Mushtaq, 2017). Bael root extracts have shown to possess anti-inflammatory properties (Benni *et al*., 2011). The fruit is a powerhouse of nutrients and bioactive compounds (Islam and Hasan, 2024; Pynam and Dharmesh, 2018; Venthodika *et al*., 2020). The fruit extracts have been found to possess anti-diabetic activity and protective effects on pancreatic tissues (Anandharajan *et al*., 2006). Anti-cancerous properties have also been attributed to bioactive compounds present in Bael (Jagetia *et al*., 2004). Bael extracts are widely used for the manufacture of herbal medicines for treating dysentery, edema, vomiting and rheumatism (Chanda *et al*., 2008). Apart from the various medicinal and therapeutic properties it is a part of Hindu mythology and mentions of this tree can be found in various ancient scriptures. The leaves of Bael are used in the worship of Lord Shiva and are routinely found in temples (Pandey *et al*., 2021; Sharma *et al*., 2007).

Bael is believed to be originated in Indian subcontinent particularly the regions encompassing Northern India, however it is widely found in Bangladesh, Nepal, Pakistan, Sri Lanka, Myanmar and Thailand (Brijesh *et al*., 2009; Sarkar *et al*., 2020; Singh *et al*., 2018; Singh *et al*., 2019). In India, Bael is found nationwide but is primarily concentrated in the eastern Gangetic plains and surrounding regions, particularly in Uttar Pradesh, Bihar, Madhya Pradesh, Chhattisgarh, and Jharkhand. It also grows in West Bengal, Punjab, and Odisha (Singh *et al*., 2018). The bael tree exhibits considerable tolerance to extreme environmental conditions, including high temperatures and low rainfall (Singh *et al*., 2018).

As, Bael is indigenous to the country a high amount of diversity is present amongst its accessions. This genetic diversity is crucial for the development of improved varieties. Most studies have been confined to characterization of Bael accessions in the North-Western and North-eastern part of India. However, the semi-arid lateritic belt of India offers significant potential for the cultivation of minor crops (Deb *et al*., 2024; Deb *et al*., 2025; Kumar *et al*., 2024). The semi-arid lateritic region of West Bengal covering the districts of Birbhum, Bankura, Purulia, and Western Bardhamman, displays significant genetic diversity among different genotypes of bael. Therefore, the present study was conducted to assess the genetic diversity present across various Bael accessions collected from different areas lying in the semi-arid lateritic region of West Bengal.

Materials and Methods

The present research was carried out during 2023-2024 and 2024-2025, focusing on fifteen distinct Bael accessions at various village locations of Birbhum district, West Bengal (India) (Table 1). Observations were taken on fruit morphology and biochemical parameters followed by genetic diversity analysis.

Fruit morphological parameters

Fully ripe fruits were randomly collected from the trees of various locations (Figure 1). Three replications were considered for each location, with every replication consisting of three fruits for assessing the morphological parameters. The fruit length was measured from the proximal end to the distal end of the fruit using a measuring scale and mean value was adjusted to millimetres. The fruit diameter was measured from the widest part of the fruit using a measuring scale and the mean value was worked out to millimetres. The number of seeds and locules per fruit were also calculated for each replication. The fruit volume was measured by water displacement method where the volume of displaced water equals to the fruit volume. The pedicel diameter was measured using vernier callipers and adjusted to millimetres from the broadest part of the pedicel. For measuring the shell thickness the pulp was removed from the fruit and the shell was cleaned. Thereafter, using vernier callipers the shell thickness was calculated from random points on the fruits and the mean was worked out in millimetres. The fruit weight, pulp weight, seed weight and gum weight were measured using pan balance and the average weight was expressed in grams.

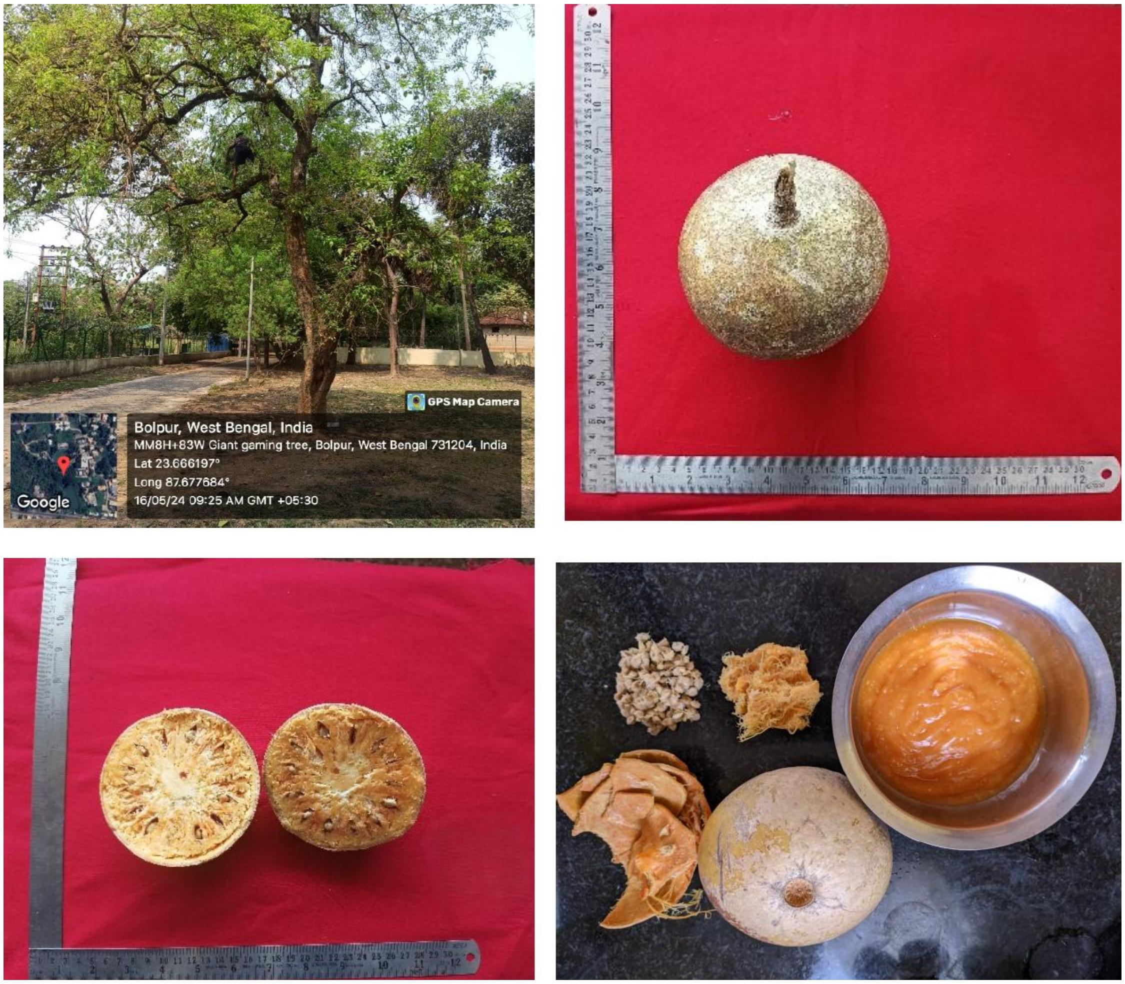

Fig. 1: Top left: Bael tree; Top right: Whole Bael fruit; Bottom left: Bael fruit cut open; Bottom right: Extraction of pulp, seeds and fibre from the bael fruit

Fruit biochemical parameters

The total soluble sugars (TSS) of the fully mature bael fruits were measured using a digital refractometer. Total sugars were measured using the method outlined in AOAC (1990). Total sugars were determined by titrating this solution in a burette against a standard mixture of Fehling's solutions A and B (1:1) with methylene blue as an indicator, noting the brick red colour as the endpoint. Reducing sugars were measured using the method described by Lane and Eynon (1923). The ascorbic acid content of the fruit was measured using the 2,6-dichlorophenol-indophenol dye titration method, as described by Ranganna (1986) where the dye is reduced to colourless form in the presence of ascorbic acid in alkaline solution. In this procedure, the dye solution was first standardized against a known concentration of ascorbic acid to determine the dye factor. The sample was then diluted with 3% metaphosphoric acid, and the resulting extract was titrated against the dye solution until a pink colour persisted for 15 seconds. Then the ascorbic acid was quantified in mg per ml using standard formula. The antioxidant activity was assessed by DPPH method where Brand-Williams *et al*., (1995). This method measures the ability of antioxidants to neutralize stable DPPH radicals. A 0.2 mL (prepared using 80% methanol) sample extract was combined with 2.5 mL of a 0.0634 mM DPPH reagent and 0.3 mL of acetate buffer (pH 5.4), and the mixture was shaken well. After incubating for 30 minutes, the absorbance was measured at 515 nm using a T80+ UV/VIS spectrophotometer (PG Instruments Ltd., UK). The percentage radical scavenging activity (RSA) was calculated using the formula: RSA (%) = (Abs0 - Abs1) × 100 / Abs0, where Abs0 represents the absorbance of the blank and Abs1 represents the absorbance of the sample. The beta carotene was estimated using the method elucidated by Davies, 1976.

Statistical Analysis

Statistical analyses of morphological, biochemical, and bioactive compound traits were carried out using mean variance analysis (Gomez and

Gomez, 1984; Frans *et al*., 2001). Analysis of variance (ANOVA) was performed for each parameter. The correlation and cluster analysis was performed with the R statistical software package (Version 4.4.1). For plotting the hierarchical clustering diagram euclidean distance was followed using the unweighted pair-group average method (UPGMA).

Results and Discussion

Fruit morphological characters

The fruit morphological parameters of all the fifteen Bael accessions are presented in Table 2. The fruit weight ranged from 206.4-972.24 gm with BA-1 exhibiting the highest fruit weight and BA-8 exhibiting the lowest fruit weight. There was a notable variation in fruit length ranging from 72.81-125.65 mm with an average fruit length of 96.82 mm. The accession BA-7 produced the smallest fruit and BA-1 produced the longest fruit in terms of length. The fruit diameter ranged from 72.17-112.96 mm, averaging at 96.69 mm, with largest diameter in BA-1 and smallest diameter in BA-8. In the case of fruit volume, BA-1 showed highest fruit volume of 950.45 ml and BA-8 showed the lowest fruit volume of 115.25 ml. The pedicel diameter ranged from 18.06 mm to 8.88 mm, averaging at 14.28 mm, with highest in BA-2 and lowest in BA-8. The shell thickness ranged from 8.69 mm to 4.16 mm with a mean shell thickness of 5.17 mm. Amongst the fifteen Bael accessions, the highest shell thickness was reported in BA-1 and the lowest in BA-13. The number of locules per fruit ranged from 10.27 (BA-8) to 14.93 (BA-3), while seed number varied between 20.24 (BA-8) and 91.43 (BA-14). In the case of shell weight, BA-1 showed the highest shell weight of 445.4 gm and BA-8 showed the lowest shell weight of 99.65 gm. Significant variability was observed in pulp weight which ranged between 92.5 gm (BA-8) to 595.15 gm (BA-11) amongst the fifteen accessions. The gum weight ranged from 21.14 gm (BA-5) to 3.53 gm (BA-9) with and mean gum weight of 11.62 gm. There was notable variability in seed weight with the highest in BA-10 (17.31 gm) and the lowest in BA-8 (3.65 gm). The fibre content ranged between 71.59 gm to 40.54 gm with a mean fibre content of 55.95 gm. The highest fibre content was noted in BA-14 and the lowest fibre content was noted in BA-8. Significant variability was also reported in edible portion of the fruit with an average edible portion of 276.06 gm, ranging between 44.34- 497.39 gm. The accession BA-11 was shown to have highest edible portion while BA-8 had the lowest edible portion.

Previous research has documented considerable variation in the morphological traits of bael fruits. Debbarma and Hazarika (2023) reported variation in fruit weight (490–1670 g), fruit length (9.68–15.66 cm), fruit volume (408.33–1288 cc), pulp weight (287.59–1343.55 g), and seed number (43.33–198) among accessions from Northeast India. Similarly, Singh *et al*. (2024) observed diversity in pulp weight (34.63–746.81 g), shell weight (10.26–225.42 g), and seed weight (5.13–46.33 g) in accessions collected from Northwestern India. More recently, Nayak *et al*. (2025) reported a wide range of fruit weight (364.67–2844.30 g), fruit length (10.87–24.27 mm), pulp weight (201–2414 g), and seed number (85–204.67) in accessions from Malda district, West Bengal. Other studies by Singh *et al*., 2025, Singh *et al*., 2024b, Pathirana *et al*., 2019, Pathirana *et al*., 2020b, Chaturvedi *et al*., 2023, Uddin *et al*., 2016 and Amulya *et al*., 2022 reported considerable variation in fruit morphological characters. Collectively, these findings indicate substantial variation in fruit morphometric traits across different bael accessions, reflecting the underlying genetic diversity. Consistent with these reports, our study also emphasizes that genetic makeup plays a greater role than environmental factors in governing fruit trait variability in Bael.

Fruit biochemical and bioactive characters

The fruit biochemical parameters of all the fifteen Bael accessions are presented in Table 3. Significant variability was observed in total soluble solids (TSS) content, which ranged from 17.2 to 36.8 ºBrix. The accession BA-10 showed the highest TSS content at about 36.8 ºBrix, while BA-1 showed the lowest TSS content of 17.2 ºBrix. Higher TSS values were also noted in BA-12, BA-14 and BA-3. In terms of acidity %, BA-9, BA-10, BA-3 and BA-15 exhibited significantly higher acidity %, while BA-2, BA-13, BA-5 and BA-11 showed lower acidity %. The TSS: acidity ratio varied significantly ranging between 33.77 to 79.75, with BA-13 showing the highest value and BA-9 showing the lowest value. The total sugar ranged between 16.27 % to 23.12% with an average of 20.54%. BA-1 exhibited the lowest total sugar % while BA-10 exhibited the highest total sugar %. Similar trend was also noticed in the case of reducing sugar % where BA-1 showed the lowest reducing sugar % and BA-10 showed the highest reducing sugar %. The ascorbic acid content (mg/100g) also varied significantly ranging between 14.93 (BA-6) to 59.7 (BA-1). Considerable variation was observed in phenolic content, ranging from 0.311 to 0.629 mg/g, with an average of 0.46 mg/g. The accession BA-5 recorded the highest phenolic content followed by BA-

12 and BA-13 while BA-15, BA-3 and BA-9 exhibited lowest phenolic content. The presence of phenolic compounds highlights the antioxidant properties of the fruit; however high content of phenols may also lead to browning of fruit due to oxidation of polyphenols. The antioxidant % ranged between 0.226 to 1.542 % with BA-1 depicting the lowest antioxidant % while BA-9 depicting the highest antioxidant %. Similarly, β-carotene content (µg/100 g) differed significantly among accessions, ranging from 122.5 µg/100 g in BA-3 to 238.4 µg/100 g in BA-15.

A TSS range of 39.96% to 30.95 % was reported by Debbarma and Hazarika, 2023 in bael accessions collected from Northeast India. They also reported significant variation in acidity (0.22% to 0.457%), total sugars (19.21% to 12.18%), reducing sugars (6.46% - 3.15%), phenolic content (3.61 mg/g to 13.7 mg/g), antioxidant content (98.89 µg/ml to 81.28 µg/ml) and ascorbic acid content (21.97 mg/100 g to 14.54 mg/100 g). A wide variation of total sugars (8.11% to 21.17%) and reducing sugars (2.51% to 9.58%) was also reported by Singh *et al*., 2024a. Other studies by, Pavani *et al*., 2018, Mani *et al*., 2017 and Singh *et al*., 2025b have also reported diversity in Bael fruits in terms of biochemical characters.

Pairwise correlation matrix of Bael accessions

Pairwise correlation analysis revealed distinct associations among morphological, physical, and biochemical traits (Figure 2). Fruit weight showed a very strong positive correlation with fruit volume (r = 0.99), fruit length (r = 0.93), fruit diameter (r = 0.91), pulp weight (r = 0.91), edible portion (r = 0.90), fibre content (r = 0.89) and shell weight (r = 0.77).

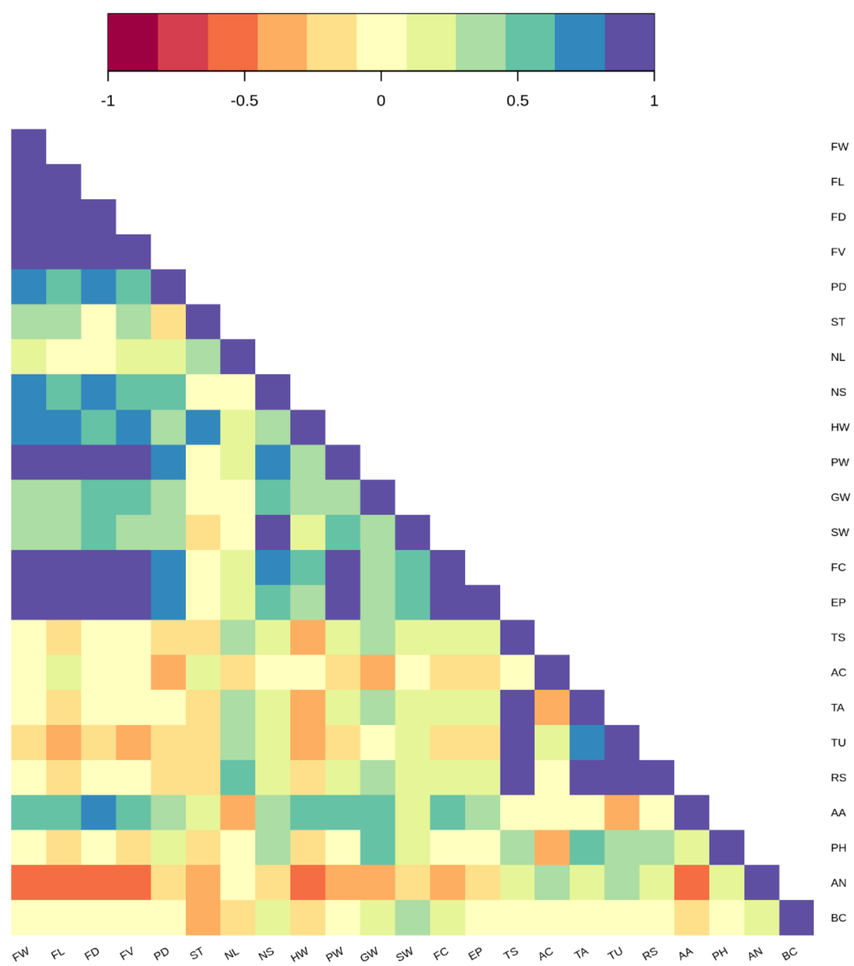

Fig. 2 : Pairwise correlation matrix heatmap of different fruit morpho-biochemical parameters of different Bael accessions

Abbreviations: FW: Fruit weight(gm), **FL**: Fruit length(mm), **FD**: Fruit Diameter(mm), **FV**: Fruit volume(ml), **PD**: Pedicel Diameter(mm), **ST**: Shell Thickness(mm), **NL**: No of Locule/Fruit, **NS**: No of Seed/ fruit, **HW**: Shell weight(g), **PW**: Pulp weight(g), **GW**: Gum Weight(g), **SW**: Seed weight(g), **FC**: Fiber content(g), **EP**: Edible portion (g), **TS**: TSS ^{o}Brix, **AC**: Acidity (%), **TA**: TSS:Acidity, **TU**: Total Sugar(%), **RS**: Reducing Sugar(%), **AA**: Ascorbic Acid(mg/100), **PH**: Phenol(mg/g), **AN**: Antioxident(%) **BC**: β-Carotene (µg/100g)

These associations indicate that larger fruits consistently contribute more to pulp and fibre yield, which are important components of the edible portion. However, fruit weight showed moderate negative correlation with TSS, Acidity, TSS: Acidity, reducing sugar % and phenol. Fruit weight showed a strong negative correlation with total sugar % and antioxidant %. This indicates that larger fruits are less sweet and contain low level of antioxidant. Other parameters like fruit length, fruit diameter and fruit volume showed similar level of association as that of fruit weight. Shell weight also exhibited a strong positive correlation with shell thickness (r = 0.81), reflecting the structural consistency of fruit pericarp. Seed number correlated positively with fruit diameter (r = 0.66) and fruit volume (r = 0.63), suggesting that larger fruits tend to carry more seeds. Pulp weight was strongly associated with fruit volume (r = 0.89), fruit diameter (r = 0.91), and fibre content (r = 0.93), highlighting that pulp yield is largely determined by overall fruit size. Fiber content was also significantly correlated with edible portion (r = 0.91), further confirming its contribution to fruit quality. Among biochemical parameters, ascorbic acid showed moderate positive correlation with fruit diameter (r = 0.69), seed weight (r = 0.45), and phenol content (r = 0.53). In contrast, antioxidant activity was negatively correlated with fruit weight (r = –0.46), fruit volume (r = –0.52), and ascorbic acid (r = –0.51), indicating an inverse relationship between antioxidant activity and fruit size or vitamin C content. Shell thickness displayed a negative association with β-carotene content (r = –0.39).

Debbarma and Hazarika, 2023 reported a strong correlation between fruit weight, fruit diameter, fruit length, shell weight and pulp weight consistent with the present study. A positive correlation was reported between phenol content and antioxidant % by Singh *et al*., 2025, which was also seen in this present study. Similar findings were also reported by Singh *et al*., 2024a, Dhakar *et al*., 2019 and Chaturvedi *et al*., 2023.

Two-way hierarchical clustering of Bael accessions

Two-way hierarchical clustering using Euclidean distance and UPGMA clustering method revealed 2 clusters (Cluster I and Cluster II) (Figure 3). Cluster I comprised of only the accession BA-1 which was grouped distinctly from all other accessions indicating its genetic dissimilarity. Cluster II formed a large cluster comprising of 2 sub clusters which was further divided into several small clusters. BA-10, BA-4, BA-14, BA-11, BA-2, BA-15 formed a single cluster within the large distinct cluster (cluster II). Similarly, BA-5, BA-13, BA-12, BA-7, BA-6 were grouped under a single cluster within Cluster II.

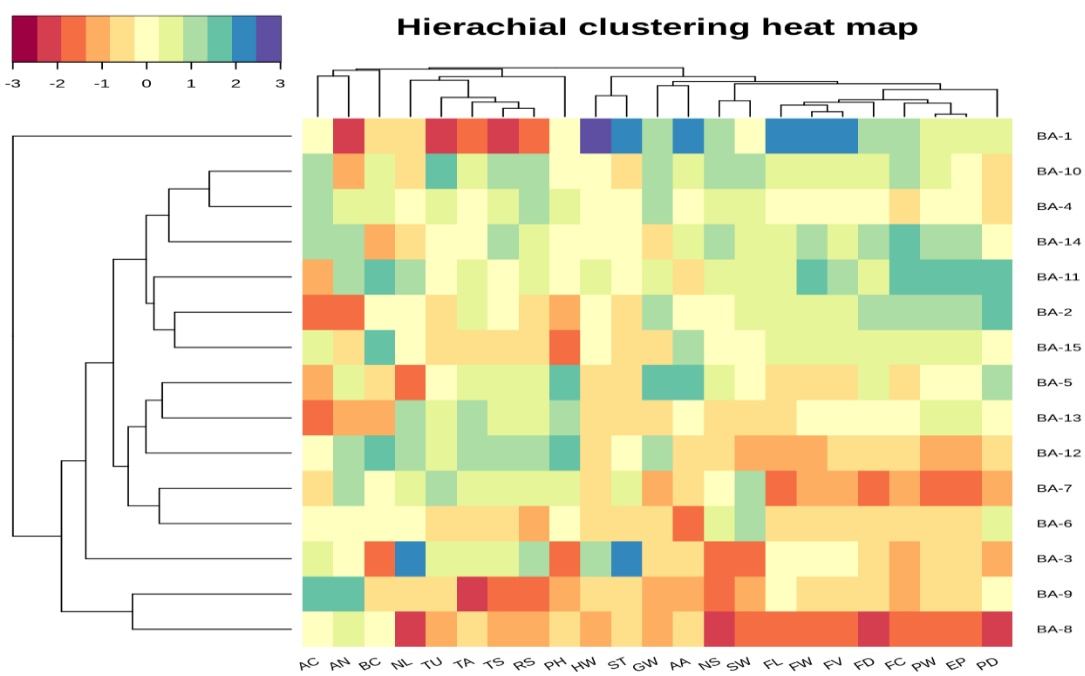

Fig. 3: Two-way hierarchical clustering heatmap of different fruit morpho-biochemical parameters of different Bael accessions
Abbreviations: FW: Fruit weight(gm), **FL**: Fruit length(mm), **FD**: Fruit Diameter(mm), **FV**: Fruit volume(ml), **PD**: Pedicel Diameter(mm), **ST**: Shell Thickness(mm), **NL**: No of Locule/Fruit, **NS**: No of Seed/ fruit, **HW**: Shell weight(g), **PW**: Pulp weight(g), **GW**: Gum Weight(g), **SW**: Seed weight(g), **FC**: Fiber content(g), **EP**: Edible portion (g), **TS**: TSS ^{o}Brix, **AC**: Acidity (%), **TA**: TSS: Acidity, **TU**: Total Sugar(%), **RS**: Reducing Sugar(%), **AA**: Ascorbic Acid(mg/100), **PH**: Phenol(mg/g), **AN**: Antioxidant (%) **BC**: β-Carotene (µg/100g)

Twenty-three variables were taken into consideration for hierarchical clustering, which showed considerable variation in contribution towards clustering of Bael accessions. The vertical clustering of variables revealed three large clusters. The variables like acidity %, antioxidant % and β-Carotene grouped under a single cluster (Cluster I) indicating a similar role in clustering of Bael accessions. Number of locule/ fruit, Total sugars, TSS: Acidity, TSS, reducing sugar and phenol content grouped under a single cluster (Cluster II). All the remaining fourteen variables grouped under a single cluster (Cluster III). The variables which are under a single cluster contribute to minimum variation in clustering of the accessions.

Our findings are consistent with the study conducted by Singh *et al*., 2025 where they analysed Bael accessions based on thirty-six different variables and reported variables like phenol content, TSS, total sugars in a single cluster. Debbarma and Hazarika, 2023 and Dhakar *et al*., 2019 also reported grouping of Bael clusters based on similarity amongst them.

Conclusion

Assessing the diversity amongst different populations is a key step in the development of improved varieties. The present study highlights the diversity present in Bael accessions collected from semi-arid lateritic belt of West Bengal. Substantial variability was observed among bael accessions for fruit morphological traits, with BA-1 generally exhibiting the largest values (fruit weight, length, diameter, volume, and shell weight), while BA-8 consistently recorded the lowest. In terms of biochemical traits like TSS, acidity, sugars, ascorbic acid, phenolic compounds, antioxidant activity, and β-carotene marked variability was seen. In future, the accessions showing better biochemical traits can be utilized in breeding, germplasm conservation, and development of nutritionally rich Bael-based products.

Table 1: Location information of the collected Bael accessions

S. No.	Accessions	Village	Latitude	Longitude
1	BA-1	Sriniketan	23º 39’ 50” N	87º 39’ 57” E
2	BA-2	Muluk	23º 39’ 14” N	87º 43’ 14” E
3	BA-3	Adityapur	23º 42’ 33” N	87º 42’ 33” E
4	BA-4	Ballavpur	23º 41’ 4” N	87º 38’ 59” E
5	BA-5	Shibpur	23º 51’ 18” N	87º 32’ 10” E
6	BA-6	Kamardanga	23º 45’ 38” N	87º 39’ 23” E
7	BA-7	Badhgora	23º 39’ 13” N	87º 41’ 10” E
8	BA-8	Ratanpur	23º 44’ 42” N	87º 42’ 33” E
9	BA-9	Jaykrishnapur	23º 40’ 20” N	87º 46’ 57” E
10	BA-10	Shyambati	23º 41’ 17” N	87º 41’ 3” E
11	BA-11	Raipur	23º 39’ 14” N	87º 43’ 14” E
12	BA-12	Faridpur	23º 41’ 54” N	87º 35’ 42” E
13	BA-13	Noadanga	23º 44’ 41” N	87º 41’ 3” E
14	BA-14	Bishnubati	23º 42’ 25” N	87º 38’ 48” E
15	BA-15	Kasba	23º 43’ 51” N	87º 39’ 22” E

Table 2: Morphological characters of different Bael accessions collected from semi-arid lateritic belt of West Bengal

SL No	Fruit weight (gm)	Fruit length (mm)	Fruit Diameter (mm)	Fruit volume (ml)	Pedicel Diameter (mm)	Shell Thickness (mm)	No of Locule /Fruit	No of Seed/ fruit	Shell weight (g)	Pulp weight (g)	Gum Weight (g)	Seed weight (g)	Fiber content (g)	Edible portion (g)
BA-1	972.24	125.65	112.96	950.45	15.96	8.69	11.44	85.35	445.4	464.71	17.59	12.41	68.84	365.87
BA-2	727.4	107.89	109.81	650.15	18.06	4.28	12.58	58.51	202.6	474.76	16.85	12.93	65.27	379.71
BA-3	579.8	98.22	92.06	460.55	11.11	8.32	14.93	31.29	278.2	265.53	6.93	4.06	46.57	207.97
BA-4	622.2	99.7	98.63	530.1	12.13	4.91	12.15	81.63	172.82	388.37	17.49	13.93	52.14	304.81
BA-5	514.8	91.3	103.87	400.3	16.25	4.22	10.27	75.72	133.45	344.19	21.14	11.42	51.23	260.42
BA-6	456.4	86.34	89.65	360.35	15.12	4.55	12.45	74.51	129.24	274.28	7.51	16.13	47.51	203.13
BA-7	357	72.81	76.41	185.75	11.88	6.16	12.67	69.44	159.62	158.22	5.16	15.66	42.68	94.72
BA-8	206.4	73.06	72.17	115.25	8.88	4.61	9.24	20.24	99.65	92.5	3.97	3.65	40.54	44.34
BA-9	425	95.84	89.08	325.25	14.5	4.38	11.79	29.82	140.76	266.34	3.53	6.11	46.29	210.41
BA-10	643.2	107.09	104.72	615.95	13.13	4.5	11.72	87.18	190.83	401.84	17.51	17.31	65.98	301.04
BA-11	870.2	106.13	106.04	765.45	17.98	4.9	13.55	82.41	244.28	595.15	13.31	14.02	70.43	497.39
BA-12	407.2	82.2	88.54	310.65	13.3	4.82	13.48	53.55	131.89	241.02	18.32	7.1	52.46	163.14
BA-13	549.2	91.01	94.19	430.25	14.49	4.16	13.77	54.45	121.25	402.25	9.23	9.39	58.37	325.26
BA-14	762.2	107.95	106.93	655.8	14.45	5.18	11.46	91.43	182.64	530.01	6.93	14.19	71.59	437.3
BA-15	637.8	107.11	105.34	550.25	14.43	4.13	11.91	70	182.95	426.26	8.97	12.25	59.48	345.56
Mean	**582.09**	**96.82**	**96.69**	**486.76**	**14.28**	**5.17**	**11.68**	**63.94**	**179.86**	**355.46**	**11.62**	**11.37**	**55.95**	**276.06**
CV	**34.53**	**14.91**	**12.47**	**45.39**	**17.45**	**27.89**	**11.05**	**35.22**	**53.45**	**38.95**	**51.93**	**38.26**	**18.75**	**45.02**
SD	**201.01**	**14.43**	**12.06**	**220.95**	**2.49**	**1.44**	**1.29**	**22.52**	**96.21**	**138.46**	**6.03**	**4.35**	**10.49**	**124.31**
Range	**206.4-972.24**	**72.81-125.65**	**72.17-112.96**	**115.25-950.45**	**8.88 – 18.06**	**4.16 -8.69**	**10.27-14.93**	**20.24-91.43**	**99.65-445.4**	**92.5-595.15**	**3.53-21.14**	**3.65-17.31**	**40.54-71.59**	**44.34-497.39**
variance	**40407.93**	**208.2613**	**145.5599**	**48829.08**	**6.21277**	**2.079921**	**1.992292**	**506.4541**	**7352.705**	**19172.53**	**36.41708**	**18.93009**	**110.0915**	**15452.48**

Table 3: Biochemical and bioactive compound characters of different Bael accessions collected from semi-arid lateritic belt of West Bengal

SL No	TSS ºBrix	Acidity (%)	TSS: Acidity	Total Sugar (%)	Reducing Sugar (%)	Ascorbic Acid (mg/100)	Phenol (mg/g)	Antioxident (%)	β-Carotene (µg/100g)
BA-1	17.2	0.46	37.39	16.27	3.89	59.7	0.486	0.226	170.1
BA-2	28.1	0.41	68.53	19.68	4.92	35.82	0.379	0.451	185.2
BA-3	34.2	0.49	69.79	21.89	5.75	26.86	0.335	0.902	122.5
BA-4	33.7	0.51	66.07	21.57	5.68	35.82	0.503	1.128	203.4
BA-5	31.5	0.43	73.25	20.85	5.38	53.73	0.629	1.135	158.6
BA-6	24.9	0.47	52.97	19.47	4.37	14.93	0.463	0.902	179.8
BA-7	31.6	0.45	70.22	22.88	5.41	23.88	0.513	1.316	191.4
BA-8	24.4	0.46	53.04	18.63	4.34	24.14	0.401	1.126	195.1
BA-9	17.9	0.53	33.77	19.64	4.09	23.64	0.371	1.542	171.7
BA-10	36.8	0.51	72.15	23.12	5.98	38.8	0.459	0.564	211.3
BA-11	31.2	0.42	74.28	20.86	5.34	23.88	0.486	1.338	235.4
BA-12	36.5	0.46	79.34	21.79	5.87	26.88	0.627	1.371	235.9
BA-13	32.7	0.41	79.75	21.37	5.55	35.78	0.561	0.678	141.8
BA-14	34.7	0.52	66.73	20.98	5.31	38.8	0.461	1.395	148.9
BA-15	27.5	0.49	56.12	19.24	4.86	44.77	0.311	0.865	238.4
Mean	**29.52**	**0.468**	**63.56**	**20.54**	**5.11**	**33.82**	**0.46**	**1.06**	**185.9667**
CV	**20.83**	**8.478049**	**22.12**	**8.62**	**13.12**	**36.17**	**20.78**	**61.14**	**26.75**
SD	**6.15**	**0.039677**	**14.06**	**1.77**	**0.67**	**12.23**	**0.09**	**0.64**	**51.54**
Range	**17.2-36.8**	**0.41-0.53**	**33.77-79.75**	**16.27-23.12**	**3.89-5.98**	**14.93-59.7**	**0.311-0.629**	**0.226-1.542**	**122.5-238.4**
variance	**37.82638**	**0.001574**	**197.745**	**3.137364**	**0.448983**	**149.7075**	**0.009141**	**0.148818**	**1238.598**

Acknowledgement: We thank all the academic, research, and administrative staff of Visva-Bharati University for all of their kind support.

Statements and Declarations: We hereby declare that the manuscript entitled "Diversity Assessment of Morphological, Biochemical, and Bioactive Traits in Bael (*Aegle marmelos* L.) under Semi-arid Lateritic Conditions" has not been published previously and is not under consideration for publication in any other journal. The work is original, and all authors have approved the manuscript for submission to this journal.

Funding: No funding from external governmental or non-governmental funding agencies has been received for the present research.

Competing Interests: P.K. Mukherjee, P. Das, U. Tudu, G.Mandal and P. Deb declare that they have no conflict of interest.

Author contributions: Pradipto Kumar Mukherjee: Writing original draft, Visualization, Methodology, Formal analysis, Data curation. Payel Das: Methodology, Formal analysis, Data curation. Urmila Tudu: Methodology.Gautam Mandal and Prahlad Deb: Writing review & editing, Validation, Supervision, Resources, Project administration, Investigation, Conceptualization

References

Amulya, R. N., Adivappar, N., Shivakumar, B. S. and Mallikarjuna, H. B. (2022). Studies on variability and correlation in bael (*Aegle marmelos* (L.) Correa). *Indian Journal of Plant Genetic Resources*, **35**, 185–188.

Anandharajan, R., Jaiganesh, S., Shankernarayanan, N., Viswakarma, R. and Balakrishnan, A. (2006). In vitro glucose uptake activity of *Aegle marmelos* and *Syzygium cumini* by activation of GLUT-4, PI3 kinase and PPARγ in L6 myotubes. *Phytomedicine*, **13**, 434–441. https://doi.org/10.1016/j.phymed.2005.03.008

Association of Official Analytical Chemists. (1990). *Official methods of analysis* (15th ed., Vol. 1, p. 83). AOAC.

Baliga, M. S., Bhat, H. P., Joseph, N. and Fazal, F. (2011). Phytochemistry and medicinal uses of the bael fruit (*Aegle marmelos* Correa): A concise review. *Food Research International*, **44**, 1768–1775. https://doi.org/10.1016/j.foodres.2011.02.008

Banerjee, A., Jain, S., Lokesh, Singh, A., Dhakad, A., Singh, A. E., Pandey, A. and Mani, G. (2024). A review: Medicinal properties and health benefits of bael (*Aegle marmelos*). *Journal of Scientific Research and Reports*, **30**, 773–786. https://doi.org/10.9734/jsrr/2024/v30i62094

Benni, J., Jayanthi, M. and Suresha, R. (2011). Evaluation of the anti-inflammatory activity of *Aegle marmelos* (Bilwa) root. *Indian Journal of Pharmacology*, **43**, 393. https://doi.org/10.4103/0253-7613.83108

Bhardwaj, R. L. and Nandal, U. (2015). Nutritional and therapeutic potential of bael (*Aegle marmelos* Corr.) fruit juice: A review. *Nutrition & Food Science*, **45**, 895–919. https://doi.org/10.1108/NFS-05-2015-0058

Brand-Williams, W., Cuvelier, M. E. and Berset, C. (1995). Use of a free radical method to evaluate antioxidant activity. *LWT - Food Science and Technology*, **28**, 25–30. https://doi. org/10.1016/S0023-6438(95)80008-5

Brijesh, S., Daswani, P., Tetali, P., Antia, N. and Birdi, T. (2009). Studies on the antidiarrhoeal activity of *Aegle marmelos* unripe fruit: Validating its traditional usage. *BMC Complementary and Alternative Medicine*, **9**, 1–12.

Chanda, R. (2008). Phytochemical and pharmacological activity of *Aegle marmelos* as a potential medicinal plant: An overview. *Internet Journal of Pharmacology*, **6**. https://doi.org/10.5580/bd

Chaturvedi, K., Kumara, U., Sane, A., Singh, P., Kumar, P. and Tripathi, P. C. (2023). Exploring the genetic diversity of *Aegle marmelos* (L.) Correa populations in India. *Plant Genetic Resources*, **21**, 107–114. https://doi.org/10.1017/ S1479262123000485

Davies, B. H. (1976). Carotenoids in higher plants. In *Lipids and lipid polymers in higher plants* (pp. 199–217). Springer.

Deb, P., Das, P., Mukherjee, P. K., et al. (2025). Morpho-biochemical and bioactive compound diversity assessment of pomelo [*Citrus grandis* (L.) Osbeck] accessions under semi-arid lateritic belt of West Bengal, India. *Vegetos*. https://doi.org/10.1007/s42535-025-01217-x

Deb, P., Mukherjee, P. K. and Das, P. (2024). Morpho-biochemical characterization of pomelo (*Citrus grandis* L.) accessions and assessment of bioactive compounds. *International Journal of Minor Fruits, Medicinal and Aromatic Plants*, **10**, 112–124.

Debbarma, P. and Hazarika, T. K. (2023). Genetic diversity of bael [*Aegle marmelos* (L.) Corr.] accessions from north-east India. *Genetic Resources and Crop Evolution*, **71**, 253–277. https://doi.org/10.1007/s10722-023-01619-3

Dhakar, M. K., Das, B., Nath, V., Sarkar, P. K. and Singh, A. K. (2019). Genotypic diversity for fruit characteristics in bael based on principal component analysis. *Genetic Resources and Crop Evolution*, **66**, 951–964. https://doi. org/10.1007/s10722-019-00757-x

Dhankhar, E., Ruhil, S., Balhara, M., Dhankhar, S. and Chhillar, A. K. (2011). *Aegle marmelos* (Linn.) Correa: A potential source of phytomedicine. *Journal of Medicinal Plants Research*, **5**, 1497–1507. https://doi.org/10.5897/ JMPR.9000048

Frans, A., DeRoon, T. and Nijman, E. (2001). Testing for mean-variance spanning: A survey. *Journal of Empirical Finance*, **8**, 111–155. https://doi.org/10.1016/S0927-5398 (01)00022-6

Gomez, K. A. and Gomez, A. A. (1984). *Statistical procedures for agricultural research*. Wiley.

Hazarika, B., Bathari, M., Upadhyay, V., Paul, S. K., Basumutary, M. U., Thengal, P. and Kotoky, U. (2020). An overview of underutilized fruit crops of Assam, India. *Journal of Applied and Natural Science*, **12**, 442–453. https://doi.org/10.31018/jans.v12i3.2343

Islam, M. R. and Hasan, S. M. K. (2024). Bael fruit-based effervescent tablet formulations: Impact on physicochemical properties. *Heliyon*, **10**, e40544. https:// doi.org/10.1016/j.heliyon.2024.e40544

Jagetia, G. C., Venkatesh, P. and Baliga, M. S. (2004). Fruit extract of *Aegle marmelos* protects mice against radiation-induced lethality. *Integrative Cancer Therapies*, **3**, 323–332. https://doi.org/10.1177/1534735404270641

Katram, N., Garlapati, P. K., Yadavalli, C., Methal, R. E., Rajappa, S. B. G. and Raghavan, A. K. (2021). *Aegle marmelos* extract rich in marmelosin ameliorates chromium-induced oxidative stress. *Journal of Food Biochemistry*, **45**, e13704. https://doi.org/10.1111/jfbc. 13704

Kumar, M., Deb, P. and Mukherjee, P. K. (2024). Fruit physicochemical and antioxidant properties of wild date palm. *Journal of Applied Horticulture*, **26**, 15–20. https://doi.org/10.37855/jah.2024.v26i01.03

Lane, J. H. and Eynon, L. (1923). Methods for determination of reducing and non-reducing sugars. *Journal of the Society of Chemical Industry*, **42**, 32–37.

Mani, A., Singh, A., Jain, N. and Misra, S. (2017). Flowering, fruiting and physio-chemical characteristics of bael grown in West Bengal. *Current Journal of Applied Science and Technology*, ***23***, 1–8. https://doi.org/10.9734/CJAST/2017 /36310

Nayak, D., Barman, P., Raman, R. K., et al. (2025). Genetic diversity of bael for physicochemical and nutritional traits. *International Journal of Fruit Science*, ***25***, 116–142. https://doi.org/10.1080/15538362.2025.2494563

Orwa, C., Mutua, A., Kindt, R., Jamnadass, R. and Anthony, S. (2009). *Agroforestree database: A tree reference and selection guide* (Version 4.0).

Pandey, D., Misra, A. K., Garg, N., Shukla, P. K., Gundappa, Shukla, S. K. and Rajan, S. (2020). *Bael cultivation*. ICAR-CISH, Lucknow.

Pandey, D., Poojan, S., Shukla, S. K., Singh, S. K. and Trivedi, A. K. (2025). Genetic diversity and antioxidant potential of bael in North India. *Plant Genetic Resources*, ***23***, 334–338. https://doi.org/10.1017/S1479262125000103

Pathirana, C. K., Gamlath, J. G. K. L., Ketipearachchi, K. W., et al. (2019). Morphological variation of bael fruits among three agro-ecological regions of Sri Lanka. *Tropical Agriculture Research*, ***30***, 23. https://doi.org/10.4038/ tar. v30i4.8326

Pathirana, C. K., Madhujith, T. and Eeswara, J. P. (2020). Bael (*Aegle marmelos* L. Corrêa), a medicinal tree with immense economic potentials. *Advances in Agriculture*, ***2020***, 1–13. https://doi.org/10.1155/2020/8814018

Pathirana, C. K., Ranaweera, L. T., Madhujith, T., et al. (2020). Assessment of elite accessions of bael in Sri Lanka. *PLoS ONE*, ***15***, e0233609. https://doi.org/10.1371/journal.pone. 0233609

Pavani, P., Harshavardhan, G., Das, S. N. and Das, B. K. (2018). Evaluation of bael genotypes for biochemical characters. *International Journal of Current Microbiology and Applied Sciences*, ***7***, 2930–2934.

Pynam, H. and Dharmesh, S. M. (2018). Antioxidant and anti-inflammatory properties of marmelosin. *Biomedicine & Pharmacotherapy*, ***106***, 98–108. https://doi.org/10.1016/j. biopha.2018.06.053

Rahman, S. and Parvin, R. (2014). Therapeutic potential of *Aegle marmelos*: An overview. *Asian Pacific Journal of Tropical Disease*, ***4***, 71–77. https://doi.org/10.1016/S2222 -1808(14)60318-2

Ranganna, S. (1986). *Handbook of analysis and quality control for fruit and vegetable products*. Tata McGraw-Hill.

Sanghi, S. B. and Mushtaq, S. (2017). *Aegle marmelos*: A potential medicinal tree. Zenodo. https://doi.org/10.5281/ zenodo.853297

Sarkar, T., Salauddin, M. and Chakraborty, R. (2020). Pharmacological and nutritional properties of bael: A critical review. *Journal of Agriculture and Food Research*, ***2***, 100081. https://doi.org/10.1016/j.jafr.2020.100081

Sharma, P. C., Bhatia, V., Bansal, N. and Sharma, A. (2007). A review on bael tree. *Natural Product Radiance*, ***6***, 171–178.

Sharma, N., Radha, N., Kumar, M. *et al*. (2022). *Aegle marmelos*: An underutilized fruit with high nutraceutical values. *International Journal of Molecular Sciences*, ***23***, 10889. https://doi.org/10.3390/ijms231810889

Singh, A. K., Singh, S. and Saroj, P. L. (2018). *The bael (Production technology)*. ICAR-CIAH, Bikaner.

Singh, A. K., Singh, S., Saroj, P. L., Krishna, H., Singh, R. S. and Singh, R. K. (2019). Research status of bael in India: A review. *Indian Journal of Agricultural Sciences*, ***89***, 1563–1571.

Singh, A. K., Yadav, L. P., K, G., et al. (2025). Genetic diversity assessment of bael varieties using morphometric, yield, and quality traits under semi-arid conditions. *BMC Plant Biology*, ***25***, 1143. https://doi.org/10.1186/s12870-025-06985-x

Singh, P., Sharma, A., Jasrotia, A., et al. (2024). Diversity in morpho-pomological attributes and biochemical profiling of bael genotypes of North-Western India. *Heliyon*, ***10***, e26525.

Singh, P., Sharma, A., Tandon, V., et al. (2024). Genetic diversity and population structure of bael genotypes using molecular markers. *Scientific Reports*, ***14***. https://doi.org/10.1038/s41598-024-69030-1

Singh, P., Sharma, A., Gupta, S. K., et al. (2025). Genotypic diversity and nutritional profiling of bael genotypes in India. *Scientific Reports*, ***15***, 31231. https://doi.org/10.1038/s41598-025-12986-5

Sonawane, A., Pathak, S. and Pradhan, R. C. (2020). Bioactive compounds in bael fruit pulp waste. *Biointerface Research in Applied Chemistry*, ***11***, 9318–9334.

Uddin, M. S., Islam, M. S., Alam, M. A. and Hossain, M. M. (2016). Study on physico-morphological characteristics of bael genotypes in Bangladesh. *International Journal of Minor Fruits, Medicinal and Aromatic Plants*, ***2***, 29–33.

Venthodika, A., Chhikara, N., Mann, S., Garg, M. K., Sofi, S. A. and Panghal, A. (2020). Bioactive compounds of *Aegle marmelos*, medicinal values and food applications. *Phytotherapy Research*, ***35***, 1887–1907. https://doi.org/10.1002/ptr.6934