

Multi-Trait Morpho-Structural Evaluation of Bamboo Species for Commercial Cultivation in Semi-Arid, Karnataka

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ABSTRACT

Using a multi-trait method 17 economically significant bamboo species were categorised based on their morpho-anatomical traits, providing a scientific foundation for selecting suitable bamboo species for plantations as a wood substitute. The traditional methodology generally includes either a single-trait methodology or a discrete scoring system, and thus results in the clustering of ranks. To overcome such problems, the analysis has been carried out by analysing six morphological traits (culm height, culm girth, length of internode, wall thickness, diameter of 5th internode and hollowness) using two different methods, discrete total scoring (1-3) and composite performance index (%). Under both methods, the best bamboo species in the present study was *Bambusa balcooa* (rank 1 based on Total Score (16) and CPI (77.99%), followed by *B. bamboos* (Total Score (15) and CPI (62.47%) and *Dendrocalamus asper* (Total Score (15) and CPI (58.20%). Both methods indicated that *B. polymorpha* (Total score = 7, CPI = 23.22%) and *B. wamin* (CPI = 34.40%) were underperforming. Nonetheless, the CPI method has given additional discriminatory power for species with intermediate rankings since the former retains continuous biological variation and breaks ties. In this regard, *Thyrsostachys oliveri* improved its standing to third-best (60.48%), while *D. longispathus* had a comparatively poor ranking due to inferior structural traits. The repeated multivariate indexation technique provides a superior means of assessing bamboo using genetic criteria compared with the traditional one-score technique.

Key words: Bamboo, Composite performance index (CPI), Multi-trait evaluation, Structural timber, Morphological grading, Core consistency

INTRODUCTION

Bamboo is one of the fastest-growing perennial grasses and has become a strategic renewable natural resource due to its rapid growth rate and high biomass productivity (Tripathi et al. 2024, Iroegbu and Ray 2021). Bamboo has been recognised as a plant that not only captures a high amount of carbon but also has many industrial applications (Ahmad et al. 2025). Around 1,600 bamboo species belonging to 125 genera have been reported to occur naturally in tropical, subtropical, and temperate climates and are sources of livelihood, restoration ecology, and the development of the green economy (Kalanzi et al. 2024, Kumar et al. 2023). Due to its versatile utility, bamboo has been increasingly recognised as an alternative to timber, steel, concrete, and synthetics in construction, furniture, engineered products, the pulp and paper industry, the textile industry, handicrafts, bioenergy, and other emerging bioproduction industries (Alamerew et al. 2026, Samsudin et al. 2025). Therefore, there is a need to identify high-yielding bamboo species suitable for different agro-climatic zones.

As the second most diverse in bamboo, India has more than 140 bamboo species distributed in various ecological zones (Khairnar et al. 2025). As part of the realisation of the potential of bamboo, national projects like the National Bamboo Mission have

been introduced in an attempt to grow bamboo on a large scale to enhance the living standards of the rural populace, agroforestry practices, restoration of degraded areas, and enhancement of the bamboo industry in India (Kumar et al. 2026). While there have been several initiatives to expand plantations, it should be noted that success in the commercial cultivation of bamboo depends on selecting the right bamboo species. The semi-arid areas in Karnataka face several environmental concerns that make it difficult to grow bamboo, owing to uneven rainfall patterns, drought periods, high evaporation and transpiration rates, and diverse soils. Even though numerous native and exotic bamboo species are available, performance is not uniform owing to genetic differences in morphological and growth characteristics. Morphological characteristics such as height, girth, internode length, diameter, wall thickness, and hollow nature influence biomass, mechanical characteristics, harvesting, transportation, processing, and industrial utilisation of bamboo (Wu et al. 2023, Zhang et al. 2024, Tesema et al. 2025).

In the past, research was mostly focused on the classification, distribution, cultivation, biomass productivity, physicochemical characteristics, or specific growth attributes of certain bamboo species. While those studies have contributed significantly to bamboo knowledge, there have been comparatively

few multi-attribute evaluations of economically valuable morphological traits across different bamboo species. Moreover, most such evaluations are conducted under humid or sub-humid climatic conditions, while evaluations of bamboo in the semi-arid region of South India are quite rare. One of the key drawbacks of current approaches is the lack of a unified methodology for integrating diverse economic attributes into a decision-support system. The multivariate method is one possible approach for analysing complex morphological differences among plant species (Li et al. 2023). Metroglyph analysis is one such approach that is easy to use in practice and provides a visual representation of the phenotypic diversity of genotypes across multiple traits (Garg et al. 2025). In combination with the Quantitative Selection Index (QSI), which combines various economic traits into a single numerical characteristic, the mentioned approach would provide a mean for objective evaluation and selection of appropriate planting material.

In this study, 17 bamboo species were evaluated based on 6 commercially important culm

characteristics: culm height, culm girth, length of the fifth internode, thickness of the fifth internode, diameter of the fifth internode, and hollowness of the fifth internode. The use of both metroglyphs and multiple-trait Selection Index used in this study aims to (i) evaluate the morphological diversity of bamboo species, (ii) classify bamboo species based on the economic value of their culm characteristics, (iii) identify suitable species that could be cultivated commercially in Karnataka, and (iv) provide a scientific basis for the selection of such species.

MATERIAL AND METHODS

Study site

The present experiment was conducted on the Bambusetum established at the Forest Research Station, Gottipura, Hoskote Taluk, Karnataka, India, under the Indian Council of Forestry Research and Education (ICFRE)-Institute of Wood Science and Technology (IWST). The experimental site lies at latitude 13.10729°N and longitude 77.84412°E, an elevation of 906.85 m amsl (Fig. 1). The forest

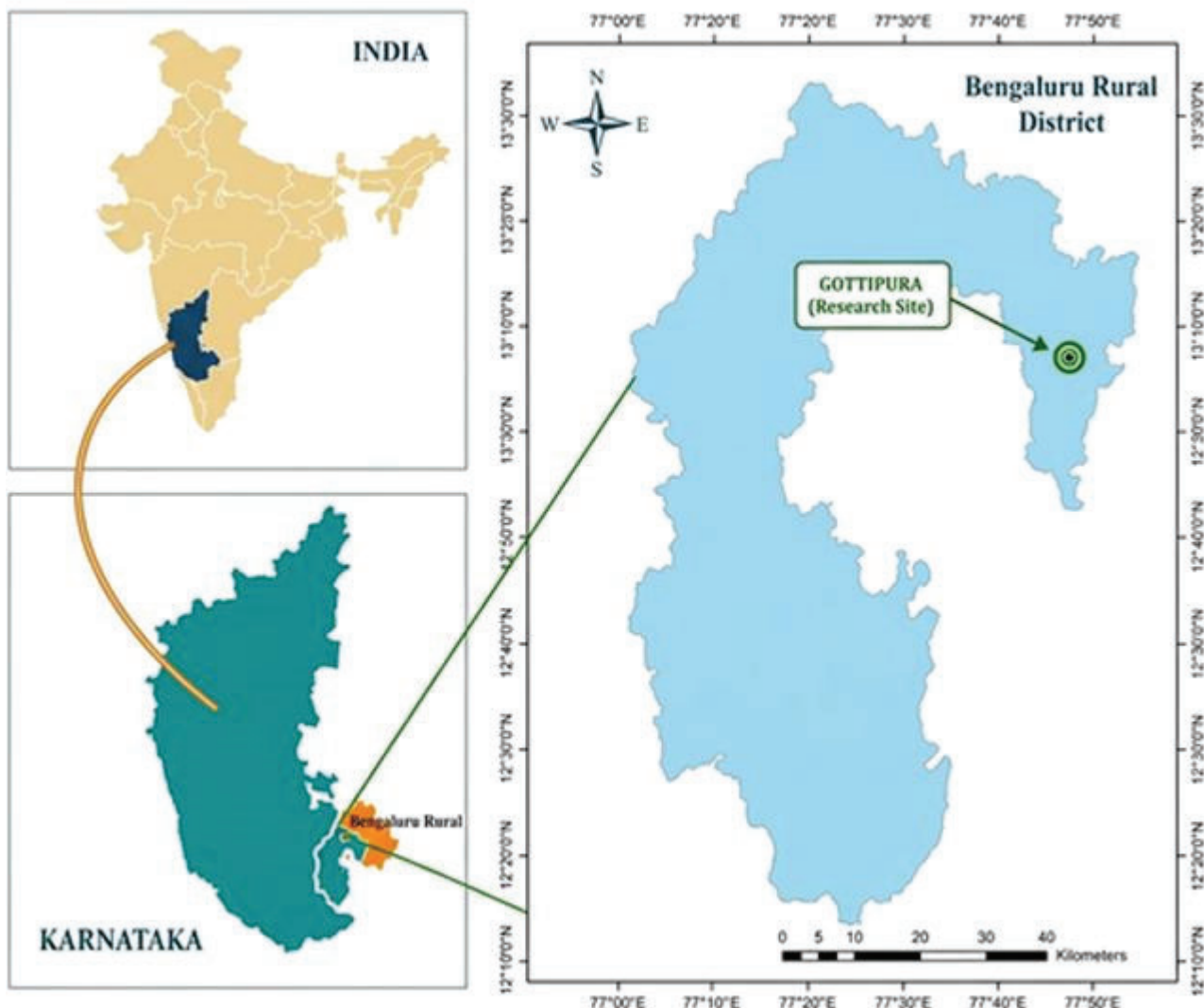


Figure 1. Location of the experimental Bambusetum at Forest Research Station, Gottipura, Karnataka, India

research station is situated in the Eastern Dry Agro-climatic Zone of Karnataka and semi-arid climatic region. The place receives an average annual rainfall of about 903 mm, which is confined to the Southwest monsoon period. The temperatures range from 18.4 to 28.4°C during the year. The soil at the site is well-drained, reddish in colour, slightly acidic to near neutral pH (6.36 - 7.03), non-saline and moderately fertile.

Plant material

The present experiment was conducted using seventeen varieties of bamboo from different genera, obtained from different regions of India and grown in a Bambusetum, established as part of the DBT-funded project initiated in 2005. The varieties of bamboo and their source from where they were collected for Babusetum are presented in Table 1.

Morphological data collection

Morphological assessment was done on all seventeen bamboo species found within the Bambusetum. Three healthy and mature culms of each bamboo species were randomly selected to avoid any variation because of differences in the age of the culms. Six different commercially significant morphological features of the culm were analysed, which included height of the culm (m), girth of the culm (cm), internode length (cm), wall thickness of the fifth internode (mm), diameter of the fifth internode (mm), and hollowness of the fifth internode (mm). Standard field forest mensuration methods were

followed when making these measurements using measuring tapes, Vernier digital callipers, etc.

Statistical analysis

All the computations for statistical analysis, normalisation of data, and calculation of final scores were done by Microsoft Excel.

Metroglyph analysis

The obtained data on different morphological parameters were analysed using the metroglyph analysis technique (Anderson 1957) to identify superior bamboo varieties based on several morphological characters simultaneously (Table 2). For quantitative traits, the data range was divided into three classes with equal intervals, and index values of 1, 2, and 3 were assigned to each class, indicating low, medium, and high, respectively. Each parameter was depicted graphically using a specific symbol, as suggested by Anderson (1957). The index values for all varieties were used to compare their morphological attributes and identify suitable bamboo varieties.

Individual trait normalisation (X_{norm})

To develop an index where the values for each trait have been measured with different units, all the values of each trait are transformed to unit-free scales between 0 and 1. For those traits that require maximisation (height, girth, internode length, wall thickness, and internode diameter):

$$X_{norm} = (X - X_{min}) / (X_{max} - X_{min})$$

Table 1. Bamboo species evaluated in the present study and their source of collection

Species	Source of collection
<i>Bambusa balcooa</i>	Rangdoi, West Bengal
<i>Bambusa bamboos</i>	Forestry College, Sirsi, UAS Dharwad, Karnataka
<i>Bambusa nutans</i>	RFRI, Jorhat, Assam
<i>Bambusa pallida</i>	RFRI, Jorhat, Assam
<i>Bambusa polymorpha</i>	KFRI, Peechi, Kerala
<i>Bambusa tulda</i>	RFRI, Jorhat, Assam
<i>Bambusa vulgaris</i> (Yellow)	Karnataka State Forest Department
<i>Bambusa wamin</i>	RFRI, Jorhat, Assam
<i>Dendrocalamus asper</i>	KFRI, Peechi, Kerala
<i>Dendrocalamus brandisii</i>	KFRI, Peechi, Kerala
<i>Dendrocalamus hamiltonii</i>	Nagaland
<i>Dendrocalamus longispathus</i>	KFRI, Peechi, Kerala
<i>Dendrocalamus stocksii</i>	Forestry College, Sirsi, UAS Dharwad, Karnataka
<i>Dendrocalamus strictus</i>	Forestry College, Sirsi, UAS Dharwad, Karnataka
<i>Gigantochloa macrostachys</i>	RFRI, Jorhat, Assam
<i>Schizostachyum dullooa</i>	Rajahmundry, Andhra Pradesh
<i>Thyrsostachys oliveri</i>	BCKV, West Bengal

Table 2. Index scores and signs for six morphological traits used in metroglyph analysis of bamboo species

Characters	MAX	MIN	CI	Score 1 value <	Sign	Score 2 value from- to	Sign	Score 3 value >	Sign
CH (m)	12.83	6.53	6.3	8.63	○	8.63-10.73	♀	10.73	♀
CG (cm)	21.73	10.73	11	14.40	○	14.40-18.07	○—	18.07	○—
IL (cm)	41.80	16.60	25.2	25.00	○	25.00-33.40	○↘	33.40	○↘
WTF (mm)	21.65	9.17	12.48	13.33	○	13.33-17.49	↘	17.49	↘
FID (mm)	64.64	29.06	35.58	40.92	○	40.92-52.78	♀	52.78	♀
HAF (mm)	35.98	11.75	24.23	19.83	○	19.83-27.91	♀	27.91	♀

Notes: CH: Culm height (m), CG: Culm girth (cm), IL: Internodal length (cm), WTF: Wall thickness at 5th internode (mm), FID:5th internodal diameter (mm), HAF: Hollowness at 5th internode (mm)

For trait to be minimised (Hollowness):

$$X_{\text{norm}} = (X_{\text{max}} - X) / (X_{\text{max}} - X_{\text{min}})$$

where X represents the value of a certain characteristic in a specific species, X_{min} represent the minimum value of that characteristic in all the species, while X_{max} the maximum value of that characteristic among all the species under study.

Composite performance index (CPI)

Since no single variable could capture the performance of bamboo, a Composite Performance Index (CPI) was developed in this study based on all measured variables. The mean of the normalised values was used to obtain CPI. This method has been widely employed in multiple trait evaluation and index studies (Smith 1936, Hazel 1943, Falconer and Mackay 1996).

The CPI (%) is computed based on the calculation of the arithmetic mean of all the normalised trait scores, multiplied by 100 for conversion into percentage form:

$$\text{CPI (\%)} = \left(\frac{\sum_{i=1}^n X_{\text{norm},i}}{n} \right) \times 100$$

Alternatively, written out completely to reflect the exact calculation from your example:

$$\text{CPI (\%)} = \left(\frac{X_{\text{Height}} + X_{\text{Girth}} + X_{\text{Length}} + X_{\text{Thickness}} + X_{\text{Diameter}} + X_{\text{Hollowness}}}{6} \right) \times 100$$

A balanced aggregation enables the index to reward or penalise individual species based on their morpho-structural balance.

RESULTS AND DISCUSSION

Index score of the morphological performance of different species

In the present study, we determined the overall structural performance of 17 bamboo species using an index score method and the scores are given in Table 3. The index score method was also employed earlier by Bhandari et al. (2012) to assess the structural performance of bamboo species. Various morphological features were considered to construct an index score to classified each species as high-performer, intermediate performer, and low-performer. *Bambusa balcooa* appeared to be the top performer among the species of the present study, with an index score of 16. This excellent score is due to its good vegetative features, which ensured the maximum cumulative score (16). *B. Balcooa* had maximum culm height (12.83 m), culm girth (21.73 cm), wall thickness (21.65 mm), and internode diameter (59.75 mm). The excellent performance of *B. balcooa* is consistent with the others reporting it as a robust, thick-walled bamboo with excellent culm properties (Jeyachitra et al. 2025).

Next to *B. balcooa*, the best-performing species included *B. bamboos*, *Dendrocalamus asper*, and *D. longispathus* with the same cumulative score of 15. These two species had shown excellent performance in terms of vegetative growth with a maximum index score (3) for culm height, culm girth, and fifth internode diameter. But both bamboo species had minimum score of 1 for wall thickness in the fifth internode. This indicates that both bamboo species have comparatively thin culm walls, even though they exhibit excellent growth performance. This

Table 3. Mean values and corresponding index scores for six morphological traits of bamboo species

Species name		CH (m)	CG (cm)	IL (cm)	WT5I (mm)	5ID (mm)	H5I (mm)	Total score
<i>B. balcooa</i>	Mean value	12.83	21.73	26.73	21.65	59.75	21.05	16
	Score	3	3	2	3	3	2	
<i>B. bamboos</i>	Mean value	10.9	17.03	26.57	19.78	57.79	20.56	15
	Score	3	2	2	3	3	2	
<i>B. nutans</i>	Mean value	9.62	15.4	32.97	13.7	43.56	17.83	11
	Score	2	2	2	2	2	1	
<i>B. pallida</i>	Mean value	10.2	16	29.87	14.08	56.18	30.57	14
	Score	2	2	2	2	3	3	
<i>B. polymorpha</i>	Mean value	7.05	10.73	31.63	9.17	35	16.28	7
	Score	1	1	2	1	1	1	
<i>B. tulda</i>	Mean value	9.34	13.37	41.8	9.87	37.06	15.82	9
	Score	2	1	3	1	1	1	
<i>B. vulgaris</i> (yellow)	Mean value	10.7	17.03	28.3	14.72	51.34	34.99	13
	Score	2	2	2	2	2	3	
<i>B. wamin</i>	Mean value	6.53	17	16.6	13.94	48.97	16.12	9
	Score	1	2	1	2	2	1	
<i>D. asper</i>	Mean value	11.65	18.67	32.8	12.91	64.64	35.44	15
	Score	3	3	30.60	1	3	3	
<i>D. brandisii</i>	Mean value	11.3	17.9	2	12.48	54.31	29.73	12
	Score	3	2	2	1	3	3	
<i>D. hamiltonii</i>	Mean value	8.85	13.97	38.07	13.56	45.68	22.5	12
	Score	2	1	3	2	2	2	
<i>D. longispathus</i>	Mean value	11	18.13	30.63	10.59	55.01	35.98	15
	Score	3	3	2	1	3	3	
<i>D. stocksii</i>	Mean value	8.53	11.43	37.33	Solid	29.06	Solid	12
	Score	1	1	3	3	1	3	
<i>D. strictus</i>	Mean value	10.23	14.97	28.03	14.53	41.29	11.75	11
	Score	2	2	2	2	2	1	
<i>G. macrostachya</i>	Mean value	11.1	17.17	23.63	13.26	53.26	26.65	12
	Score	3	2	1	1	3	2	
<i>S. dullooa</i>	Mean value	9.65	15.47	30.37	14.5	46.68	21.43	12
	Score	2	2	2	2	2	2	
<i>T. oliveri</i>	Mean value	9.95	15.97	35.5	17.16	50.27	13.56	12
	Score	2	2	3	2	2	1	

shows that while the growth performance of both these bamboo species is excellent, their thinness in wall thickness may pose a problem for the structural performance of the bamboo culms in areas requiring high culm strength. The performance of *D. asper* is similar to that reported by others, which describes it as fast-growing and producing large-diameter bamboo (Sumardi et al. 2025). Both *B. pallida* and *D. brandisii*, have a cumulative score of 14, indicating an excellent combination of vertical growth and culm physical attributes. *D. brandisii* was suggested as a species of bamboo that is very versatile and is widely used for construction, crafting, scaffolding,

the manufacture of furniture, and pulp because of its long (13-20 m) but moderately thick (5-8 cm) culms (Manasa et al. 2023).

The good cumulative score of *B. pallida* (14) was consistent with its various uses in house construction, basketry, mat-making, toys, panel walls, and the pulp and paper industry (Beena and Rathore 2012). The bamboo species *B. vulgaris* (yellow) had a cumulative score of 13 and thus exhibited architectural properties, as indicated by the high hollowness index. Other high performing species clusters had a total cumulative score of 12 and comprised the species *D. hamiltonii*, *D. stocksii*,

G. macrostachya, *S. dullooa*, and *T. oliveri*. The medium-performing species included *D. stocksii*, which had some unique structural features. Even though it had scored the lowest index scores (1) in the aspect of culm height and culm girth, *D. stocksii* had scored maximum (3) index scores in the aspects of internodal length, wall thickness, and culm hollowness. Even though *D. stocksii* is not among the high-performing species cluster, its distinctive culm structure makes it ideal for various uses. This is supported by Rane et al. (2016), who observed that *D. stocksii* is a thornless, medium-sized bamboo with almost solid culms and is therefore well adapted for domestication as a multi-purpose bamboo in Peninsular India.

Both, *D. hamiltonii* and *T. oliveri* with their long internode length (score 3) maintained a moderate composite score (12). The characteristic of having a relatively long internode length is certainly in conformity with the morphology of these two species, especially *D. hamiltonii* and *T. oliveri*, because it is stated that *T. oliveri* has culms with long internodes that facilitate rapid elongation (Kumar et al. 2001). This classification concludes with the lowest-performing ones, each with a Total composite Score of 11, due to their mid-range phenotypic traits across all morphological attributes. These least performing species are identified by their lack of vegetative/asymmetric structures. Both *B. tulda* and *B. wamin* had a total of 9 as composite score. While *B. tulda* had an excellent longitudinal growth rate, with the maximum internode length (41.8 cm; Score 3), its overall standing has been affected by poor radial growth, as it scored 1 for girth, wall thickness, and diameter. *B. wamin*, which grew oppositely to *B. tulda* because it was dwarf, as indicated by a high culm girth (Score 2), although the culm height was relatively low (6.53 m; Score 1). This observation proves the growth habit of *B. wamin* discussed by Banik (2020). *B. polymorpha* had the lowest Total Score of 7 due to having the minimum growth parameters (Score 1) in five out of six criteria (Table 3). Though an index classification based on a combination of several criteria demonstrates that the Index Score is well-balanced and provides a clear direction for selecting species for specific purposes (Thapa et al. 2025).

Quantitative analysis of the composite performance index (CPI %)

Application of the multi-trait Composite Performance Index (CPI) technique was highly effective in converting the various physical measurements into a standardised dimensionless index, thus giving rise to a hierarchy among the 17 species of bamboos studied (Table 4). *B. balcooa* was the best performing in the category of architecture, as it had a CPI value of 77.99%. This bamboo was dominant due to its well-balanced construction, as it achieved

the highest score (1.00) across all three physical parameters, i.e., culm height, culm girth, and culm wall thickness. *B. bamboos* (CPI 62.47%), *T. oliveri* (CPI 60.48%) and *D. asper* (CPI 58.20%) were included in the superior secondary cluster. However, despite *D. asper* having the highest radial growth and internode diameter (1.00), the modification in the structure of *D. brandisii* helped it to be classified in the excellent five-cluster group (CPI 51.89%) as its superior vertical and girth growth (0.76 and 0.65, respectively) outweighed the lower wall thickness (0.27). The mid-range cluster lies between CPI 43 and 48%.

D. stocksii (CPI 43.89%) had the maximum score (1.00) due to a perfect culm profile consisting of a fully solid structure with no cavity. However, its CPI was determined by the poor growth rates in culm girth (0.06) and culm diameter (0.00). Similarly, *B. tulda* (CPI 42.12%) had the maximum internode length score (1.00) but had poor wall thickness (0.06). Both *B. wamin* (CPI 34.40%) and *B. polymorpha* (CPI 23.22%) had low CPI. The suitability of bamboo for industrial applications depends on the overall expression of its physical qualities rather than on a single quality. This explains the need to consider the Composite Performance Index (CPI), which combines height, girth, internode, wall thickness, and hollowness of bamboo stems into a single index.

Cross-methodology consistency and compatibility

The comparison of the two index models shows an exceedingly high degree of core consistency in selecting the most elite species in a bambusetum, despite slight discrepancies in the ranking. The traditional discrete model and the continuous CPI % model showed a high degree of confidence in defining *B. balcooa* as the elite species growing in the bambusetum and ranked it first in both models (Total Score: 16; CPI: 77.99%) followed by *B. bamboos* (Total Score: 15; CPI: 62.47%) and *D. asper* (Total Score: 15; CPI: 58.20%), indicating that they are very hardy species. On the other hand, at the lowest end, there was perfect agreement between the two models for *B. polymorpha*, with a total score of 7 and a CPI of 23.22%, alongside *B. wamin* (34.40%). The most prominent disparity between the two assessments was for *T. oliveri*, which appeared as a member of a multi-species tie of 12 species using the traditional score, but rose to 3rd overall with a CPI of 60.48%. Conversely, *D. longispathus*, which appeared as one of the top performer with a Total Score of 15, dropped down considerably to CPI 46.37% when the weaknesses in its physical characteristics were taken into account. The comparison of the methods shows that while both methods agree on the choice of the best and worst bamboo species, the latter (CPI%) method is clearly superior at revealing concealed performance and adjusting inflated scores for mid-range varieties.

Table 4. Normalized Trait Scores and Final Composite Performance Index (CPI)

Species	CH	CG	IL	WT5I	5ID	H5I	CPI (%)
<i>B. balcooa</i>	1.00	1.00	0.40	1.00	0.86	0.41	77.99
<i>B. bamboos</i>	0.69	0.57	0.40	0.85	0.81	0.43	62.47
<i>T. oliveri</i>	0.54	0.48	0.75	0.64	0.60	0.62	60.48
<i>D. asper</i>	0.81	0.72	0.64	0.30	1.00	0.02	58.20
<i>D. brandisii</i>	0.76	0.65	0.56	0.27	0.71	0.17	51.89
<i>B. pallida</i>	0.58	0.48	0.53	0.39	0.76	0.15	48.24
<i>D. strictus</i>	0.59	0.39	0.45	0.43	0.34	0.67	47.88
<i>G. macrostachya</i>	0.73	0.59	0.28	0.33	0.68	0.26	47.62
<i>B. nutans</i>	0.49	0.42	0.65	0.36	0.41	0.50	47.33
<i>S. dullooa</i>	0.50	0.43	0.55	0.43	0.50	0.40	46.65
<i>B. vulgaris</i> (yellow)	0.66	0.57	0.46	0.44	0.63	0.03	46.62
<i>D. longispathus</i>	0.71	0.67	0.56	0.11	0.73	0.00	46.37
<i>D. hamiltonii</i>	0.37	0.29	0.85	0.35	0.47	0.37	45.14
<i>D. stocksii</i>	0.32	0.06	0.82	0.43	0.00	1.00	43.89
<i>B. tulda</i>	0.45	0.24	1.00	0.06	0.22	0.56	42.12
<i>B. wamin</i>	0.00	0.57	0.00	0.38	0.56	0.55	34.40
<i>B. polymorpha</i>	0.08	0.00	0.60	0.00	0.17	0.55	23.22

Note: CH: Culm height, CG: Culm girth, IL: internodal length, WT5I: wall thickness at fifth internode, 5ID: fifth internodal diameter, H5I: hollowness at fifth internode

CONCLUSIONS

The present study indicated that the use of a multiple-trait assessment approach is a useful and reliable technique for evaluating the morpho-structural performance of 17 commercially important bamboo species. The novel Composite Performance Index (CPI%) provided greater precision than the traditional method by preventing rank clustering and enabling differentiation among bamboo species with similar performance levels. *Bambusa balcooa* proved to be the best performer (77.99%), followed by *B. bamboos* (62.47%), *Thyrsostachys oliveri* (60.48%), and *Dendrocalamus asper* (58.20%), which can be used as the best candidates for replacement of structural timber, biomass production, and agro-industry. In addition, the CPI% helped to resolve some ranking inconsistencies associated with the traditional scoring approach, especially in evaluating the higher performance level of *T. oliveri* and eliminating the overrating of *D. longispathus*. At the same time, *B. polymorpha* (23.22%) and *B. wamin* (34.40%) were shown to have low structural potential and are suitable for ornamental use. Thus, the results presented here indicate that the integration of multiple morpho-structural characteristics into a single continuous composite index enables the selection of the best bamboo species more objectively, precisely, and reliably.

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