Mechanical Characterization of Bamboo Pole for Building Engineering: A Review

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Bamboo is a sustainable and cost-effective alternative to traditional construction materials. Despite the fact that three species are well known for structural applications, namely *Dendrocalamus asper*, *Gigantochloa scortechinii*, and *Gigantochloa levis*, the scientific data for their mechanical characterization is scarcely available and widely dispersed. In addition, a systematic literature review appraising the study advancement of mechanical characterization of bamboo had been unavailable. This paper bridges this gap by conducting a systematic literature review (SLR) of the available literature of mechanical characterization of bamboo pole. A total of 54 relevant articles were retrieved from Scopus and snowballing and then put forward through bibliometric analysis using VOSviewer. The results showed that the distribution of data for physical and mechanical characterization of aforementioned species was scattered due to the different location (origin), age, and initial moisture content recorded during empirical work among the researchers. This review's importance and distinctiveness lie in its synthesis of the existing literature on bamboo mechanical characterization. The findings provide a point of reference for both academia and industry by bridging the scarcity of current bamboo engineering data and outlining future possibilities for bamboo research in the building and construction domain.

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INTRODUCTION

Bamboo is a natural fiber composite used for household application, furniture, and food (Azmy *et al*. 1991; Yap *et al*. 2017). This natural fiber could substitute the synthetic fiber reinforced plastic because it is more durable, economical, and sustainable for green building (Mansor *et al*. 2019). An *et al.* (2020) found out that the mechanical strength of material bamboo (bamboo fiber) is an excellent fit for paper products. Also, bamboo is a promising material for producing bicycle frames and fabrics because of its mechanical strength applicability (Tausif *et al.* 2014; Jakovljevic *et al.* 2017). In addition, the developed CTNF-BACNF nanocomposite has good mechanical properties, thermal stability, and biodegradability, and is promising for food packaging (Hai *et al.* 2019). Bamboo is the fastest growing plant; it matures within 3 to 4 years (Wahab *et al*. 2012).

Physical characteristics of bamboo such as age, height, moisture content, thickness, diameter, relative density, and shrinkage depend on the species, soil, climate conditions, and harvesting technique (Lee *et al*. 1994). Although the physical properties have been scarcely investigated (Liese 1985; Amada *et al*. 1997; Azmy *et al*. 2009; Asari and Suratman 2010; Wahab *et al*. 2010; Mohamed *et al*. 2011; Sakaray *et al*. 2012; Waranyu *et al*. 2013; Anokye *et al*. 2014a; Ye and Fu 2018), mutual data derivation has proposed that the age and height of bamboo have different effects depending on the bamboo species.

Several studies showed that moisture content affects the mechanical strength properties. In air-dry conditions, a moisture content of 12% is the nominal value (Chinese Standard Agency 2007). However, this suggestion is still open for discussion because the mechanical characterization needs to be justified (Janssen 1985; Godbole *et al*. 1986; Hisham *et al*. 2006; Hamdan *et al*. 2009; Wakchaure and Kute 2012; Anokye *et al*. 2014b; Awalluddin *et al*. 2017; Li *et al*. 2017; Ismail *et al*. 2019). The grading properties of bamboo consist of thickness, diameter, and density. The thickness of the bamboo wall culm is the average of four measurements taken around the circumference of the culm at angular spacings of 90º (ISO/TC 165 N 1120 2018). The thickness of bamboo decreases along the culm height (Amada *et al*. 1997; Awalluddin *et al*. 2017). The wall thickness at the base of all culms seemed bigger and thicker against the age factor (Mohamed *et al*. 2011), although this result is debated (Hisham *et al*. 2006). The mean diameter-at-breast-height (DBH) is different for each species and age (Mohamed *et al*. 2011), but the *Gigantochloa* species shows the same mean DBH, which is insignificant against age factor (Asari and Suratman 2010). There is a correlation between bamboo species and density, such that *Gigantochloa scortechinii* has recorded a higher density than the *Bambusa vulgaris* (Hisham *et al*. 2006; Nordahlia *et al*. 2012; Anokye *et al*. 2014a). The density is inversely proportional to the moisture content (Hamdan *et al*. 2009; Wahab *et al*. 2012; Anokye *et al*. 2014a; Awalluddin *et al*. 2017; Yap *et al*. 2017). Scientific data for shrinkage (radial, tangential, and volumetric) has been recorded (Wahab *et al*. 2012; Razak *et al*. 2013; Edi Suhaimi *et al*. 2014), though further exploration is needed.

The recorded shear strength for bamboo has suggested the increment in strength from green to air-dry conditions due to the reduction of moisture content (Rafidah *et al*. 2010; Wahab *et al*. 2012). Mokhtar *et al*. (2018) has suggested a different perspective with specific allocation of green and air-dried condition in proclaiming the bamboo shear strength. Studies on bamboo tensile strength have suggested that *Dendrocalamus asper* is the top of the list (Awalluddin *et al*. 2017; Amatosa and Lorento 2018; Jais *et al*. 2020), while *Gigantochloa levis* shows higher tensile strength than *Gigantochloa scortechinii*. However, more investigation is needed to expand the quality of deducing this outcome for bamboo strength grading in the future. Studies that observed the compressive strength of bamboo have suggested that the optimized moisture content to achieve compression strength fairly ranges between 12% to 15% (Awalluddin *et al*. 2017; Mokhtar *et al*. 2018).

The vast amount of bamboo research makes it difficult to evaluate the dimension of the knowledge discovered, in particular synthesizing the mechanical characterization of bamboo pole, its critical domains, and emerging trends. The findings have focused on the silo mentality context of physical and mechanical properties of bamboo without further synthesizing the extending overall mechanical characterization aspects of bamboo. Such an exercise on bamboo engineering is important to provide a point of reference for guide scholars and practitioners to enable mainstreaming of bamboo material knowledge and practice.

To address the above-mentioned deficiency, a schematic literature review is established in the present work to explore more justification and knowledge exploration related to mechanical characterization of bamboo pole, specifically, *Dendrocalamus asper*, *Gigantochloa scortechinii*, and *Gigantochloa levis*. Hence, this paper aims to perform a bibliometric analysis of the documents published related to bamboo strength specification as to review the current research status using VOSviewer. The purposes of this systematic literature review are as follows: (1) to summarize the trends in bamboo research of specified species from the perspective of a co-occurrence network; (2) to determine physico-mechanical characterization of bamboo; and (3) to identify bamboo failure mechanisms in correlation with the physical and mechanical properties of bamboo as a future research roadmap. This paper is structured to review the physical and mechanical characterization of bamboo poles from previous compilation of related literature.

RESEARCH METHOD

A schematic literature review (SLR) was used in this study to review the specified species bamboo pole's mechanical characterization critically. All the data was obtained from previous studies. Hence, there is no experimental work and finite element analysis conducted in this research. This method employs a thorough review strategy to capture works focusing on the specific context and further synthesizing the findings into several perspectives depending on each study's objective. Osei-Kyei *et al*. (2015) used a three-stage search approach to undertake a content analysis of the mechanical characterization of the specified species bamboo pole. The three stages comprise identifying database and journal selection, targeted article selection, and content analysis. A framework of this approach is shown in Fig. 1.

Identification (Database and Journal Selection)

In stage 1, all the journals were searched and downloaded from the Scopus database, as it tends to have the most significant search engines in regard to their breadth and precision of coverage. Scopus has been used in many recent reviews in bamboo studies. For example, it was used to review the strength parameters of parallel to fiber (de Jesus *et al*. 2021), water absorption behavior of bamboo (Salih *et al*. 2019), and interactive buckling of bamboo structure (Awalluddin *et al*. 2019). In order to carry out the search, the Scopus search engine was utilized by using "titles/abstract/keyword" as the first step. The keywords of "bamboo", "culm", "mechanical characterization", "mechanical properties", "physical characterization", "physical properties", and "strength of bamboo" were considered when doing the first search to identify papers. "Article or Review" was selected as the document type during setup. The search string TITLE-ABS-KEY ("bamboo" OR "culm" OR "mechanical characterization" OR "mechanical properties" OR "physical characterization" OR "physical properties" AND "strength of bamboo") was employed to find results for all bamboo species used in structural applications.

Because this study analyzed mechanical characterization related to bamboo literature, the keywords were intentionally diverse to capture a comprehensive picture of the features of bamboo that are relevant to its mechanical and physical characterization. After the keywords were entered, the screening of the publication source was restricted to only looking at English-language journals. The publication date also was limited to the past 16 years, from 2005 to 2021. The journals and proceedings were taken as the sample in this study due to the lack of articles related to bamboo studies. The original search yielded a total of 195 publications, which were narrowed down to 125 articles. Table 1 displays the various publications that were deemed acceptable following the initial screening.

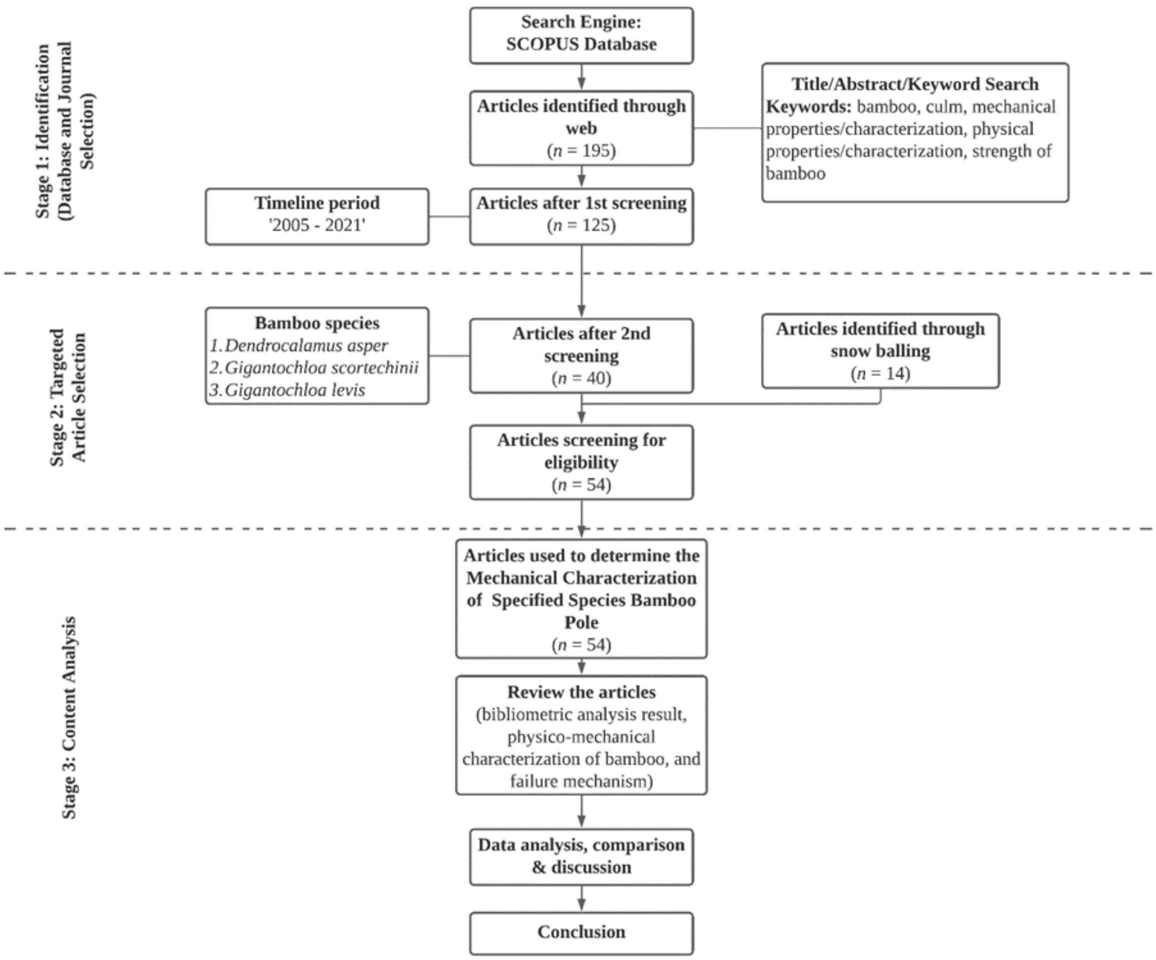

Fig. 1. Methodology for conducting a systematic review

Targeted Article Selection

In stage 2, the process selection of articles was carried out in order to examine the articles. This method reduced unrelated articles and focused more on the main objective of the study. Three inclusion criteria were applied to the article selection process.

To begin, the article must be focused on physical and mechanical characterization of the bamboo pole. The physical characterization must include one of the criteria, which are age, height, moisture content, thickness, diameter, specific density, and shrinkage. Meanwhile, the scope for mechanical characterization was shear strength, tensile strength, compression strength, modulus of rupture, and modulus of elasticity.

Second, the article should have at least one species of bamboo related to *Dendrocalamus asper* (Buluh betong), *Gigantochloa scortechinii* (Buluh semantan), and *Gigantochloa levis* (Buluh beting). Lastly, the article should include any relevant information on physical and mechanical characterization of three bamboo poles species.

A list of all publications that did not meet the aforementioned standards was compiled. Due to this screening, papers that were not relevant, such as articles that focused on alternative contexts, like engineered bamboo, were eliminated. While study of properties through-thickness of bamboo (inner, middle, and outer) are beyond the scope of this study. Consequently, the contents of the articles were examined, and the number of the articles was reduced to 40, which were then used for the content analysis in determining the mechanical characterization of specified species bamboo poles.

Table 1. The Breakdown of the Number of Articles in Stage 1

Type	Journal Name	Frequency
Journal	*Construction and Building Materials*	16
	Journal of Bamboo and Rattan	10
	Journal of Wood Science	6
	BioResources	6
	European Journal of Wood and Wood Product	6
	Journal of Tropical Forest Science	6
	Wood Science and Technology	5
	Composites Part B: Engineering	5
	Engineering Structures	4
	Annals of Botany	4
	Journal of Mechanical Behaviour of Biomedical Material	3
	Malaysian Forester	2
	Industrial Crops and Products	2
	Flora: Morphology, Distribution, Functional Ecology of Plants	2
	Journal of the Indian Academy of Wood Science	2
	Journal of Materials in Civil Engineering	2
	Materials and Structures	2
	Journal of Forestry Research	2
	Forest Product Journal	2
	Journal of Materials in Civil Engineering	2
	Materials and Design	2
	Others*: *Journal of renewable materials*, *Philippine Journal of Science*, *Frontiers in Materials*, etc.	31
Proceeding	*Institute of Physics Conference Series*	1
	IFMBE Proceedings	1
	Proceedings of 1st International Conference on Modern Bamboo Structures, ICBS-2007	1
* One article per journal		

As there was still a lack of articles found, additional related articles that were not captured by the Scopus database were identified using the "snowball" method. The term "snowball" means that certain studies were found due to their being cited in other works that had been found according to the search procedure outlined above. As a result, 14 articles were identified using the same criteria through the snowballing method. This method was carried out to supplement the results of the first two-stage search in order to have a complete view of the papers that merited further study. The snowball exercise is sufficient since it provides the option to include significant state-of-the-art works connected to the subject (Li *et al*. 2019).

Content Analysis

The qualitative research method was used in this study. Qualitative research collects data, information and analyzes non-numerical data to understand concepts, opinions, or experiences.

In stage 3, following the identification and selection of articles, a comprehensive examination of their content was conducted. A total of 54 articles were used in determining the mechanical characterization of the specified species bamboo pole. It is important to note that any numerical data or a detailed description of the topic related to the mechanical characterization of specified species bamboo poles were figured out based on the total number of articles that were taken into consideration for the content analysis. The information in the articles was extracted and reviewed based on the scope of this study.

The selected articles were reviewed based on the following contents. The findings of the bibliometric analysis consisted of the physical (age, height, diameter, thickness, moisture content, density, and shrinkage), mechanical characterization (shear strength, tensile strength, compressive strength, and bending strength), and the failure mechanism of three species bamboo pole. VOSviewer software was used for the bibliometric analysis. Due to the limited resources, this free-accessible software was merely considered. Additionally, this VOSviewer can visualize the networks at a big scale and speed by using manual methods or software tools. It also has text mining capability, by which network maps of co-occurring keywords sourced from abstracts and bodies of research articles can be constructed. The criteria of the three-stage search approach can only be undertaken visually by VOSviewer, as can be seen from other researcher's work (Che Ibrahim *et al.* 2021). The results were compared and summarized by the specific category.

RESULTS AND DISCUSSION

Bibliometric Analysis Result

Analysis of co-authorship

Regarding the statistics in Table 2, the five major quantitative measurements of selected authors who published more than two articles consist of the number of articles, total citations, average publication year, average citations, and average normalization citations. The measurements present the research output and influence of the given authors on the research fields. The analysis indicates that 13 authors got involved in more than one article. In addition, 56 total citations were recorded as the highest citations of articles. The total citations measure the influence and impact of the research work.

Table 2. Detailed Information of the Selected Authors

Author	Number of Articles	Total Citations	Average Publication Year	Average Citations	Average Norms. Citations
Wahab r.	5	46	2010	9.2	1.75
Hamdan h.	4	52	2008	13	1.16
Anwar u.m.k.	3	51	2008	17	1.21
Zaidon a.	3	51	2008	17	1.21
Tarmizi m.m.	2	56	2007	28	1.82
Othman s.	2	43	2008	21.5	1.75
Sulaiman o.	2	39	2008	19.5	1.11
Mohamad a.	2	27	2007	13.5	1.59
Samsi h.w.	2	27	2007	13.5	1.59
Mohd tarmizi m.	2	23	2009	11.5	1.82
Salam m.a.	2	16	2013	8	2.02
Rasat m.s.m.	2	16	2013	8	2.02
Mustafa m.t.	2	16	2013	8	2.02

The average publication year of authors showed that the articles were developed between the year 2007 to 2013. It is worth noting that essentially more research studies in characterizing the mechanical properties of bamboo poles are needed for the specified species that is useful for building construction.

Analysis of co-occurrence of keywords

Contents of the 54 target articles were analysed following the initial inspection of keywords. Main keywords addressed in each article were extracted as shown in Table 3.

Table 3. Main Keywords of Mechanical Characterization of Bamboo Poles

Keyword	Occurrences	Average Publication Year	Average Citations	Average Norms. Citations
Gigantochloa scortechinii	15	2012	12	1.25
Mechanical properties	15	2015	8.67	1.16
Moisture content	13	2012	12.67	1.03
Physical properties	8	2013	14.88	1.44
Tensile strength	8	2018	5.38	1.19
Bambusa	7	2012	8.86	2.15
Fibers	7	2015	9	1.03
Dendrocalamus asper	6	2016	6	1.77
Tensile testing	5	2017	5.40	0.61
Bambusa vulgaris	4	2015	16.25	1.67
Compression strength	4	2017	5.25	0.44
Density (specific gravity)	4	2013	12.50	1.35
Gigantochloa	4	2012	9.50	2.50
Modulus of rupture	4	2015	6.75	1.78
Shrinkage	4	2013	11	1.23
Strength	4	2011	11.50	1.83
Water absorption	4	2016	16.75	1.45
Different heights	3	2017	6.67	2.43
Durability	3	2012	10	1.12
Height	3	2017	7.33	2.44
Radial shrinkage	3	2016	6	1.69
Tangential shrinkage	3	2016	7.67	2.07

The keywords ‘*Gigantochloa scortechinii*’ and ‘Mechanical properties’ have received high attention in this research field, with 15 occurrences. That was followed by moisture content, with 13 occurrences, while physical properties and tensile strength had the same occurrence, which is 8, respectively. Besides, the average publication year illustrates that the most related study topics of the mechanical characterization of bamboo poles were raised around these five years, 2012 to 2017. The highest average year published was in 2012 with keywords ‘moisture content’, ‘*Gigantochloa scortechinii*’, ‘*Bambusa*’, ‘*Gigantochloa*’, and ‘durability’. In contrast, tensile strength keywords record as the lowest average year published was in 2018. This shows that the significance of related research topics has been reduced over the years. Based on Fig. 2, a large node size indicates high occurrence of the items, and a thick connection line indicates close relationship between two items. Different colors divide nodes into different clusters. The keywords consist of four clusters such as *Gigantochloa scortechinii*, mechanical properties, physical properties, and tensile strength, and are seen through the large node of different colors. The network visualization of co-occurrence of keyword analysis indicates that the interconnections of keywords between the clusters are strongly connected.

Analysis of countries' activeness

In Table 4, the details of countries or regions for the research origins of published mechanical characterization of bamboo poles are listed along with the number of articles, total citations, average publication year, average citations, and average norm citations.

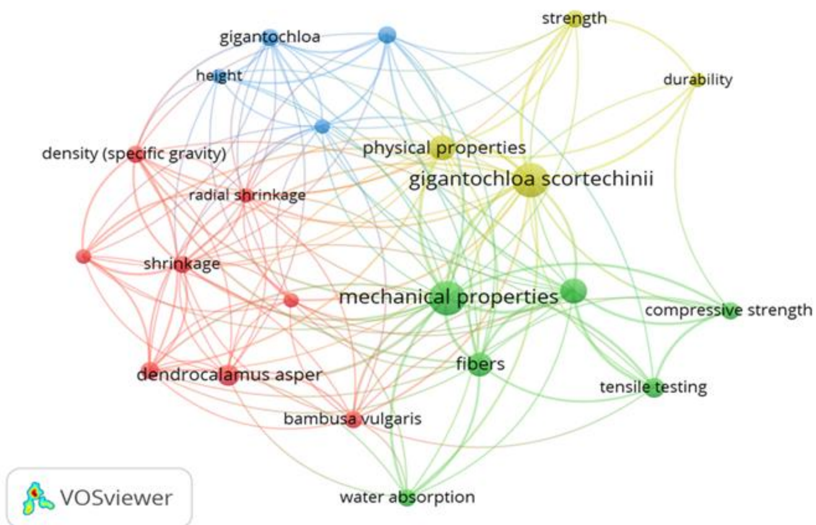

Fig. 2. Network visualization of co-occurrence of keyword analysis

Table 4. Countries or Regions of Mechanical Characterization of Malaysian Bamboo Poles

Country	Number Of Articles	Total Citations	Average Publication Year	Average Citations	Average Norms. Citations
Malaysia	32	233	2013	7.28	0.93
Philippines	5	96	-	-	-
Thailand	3	24	-	-	-
South Korea	2	18	2018	9	0.33
Germany	2	16	-	-	-
Indonesia	5	5	2018	1	0.23

Malaysia has the largest representation, with the highest number of articles and total citations. This is followed by the Philippines and Indonesia with the same score of 5 number of articles but the different number of citations, 96 and 5 citations, respectively. The distribution of countries shows that the studies related to the mechanical characterization of bamboo poles of that specified species still are lacking in research and are not expanding. This also has been mentioned by Awalluddin *et al*. (2017) that one of the factors that contributes to low utilization of bamboo properties is a low number of relevant studies by the researchers. Most of the countries that encourage research in the field are within the Southeast Asia region, although it is worth noting that Germany stands out as one of the European countries that has shown interest in exploring technical data of the mechanical properties of bamboo pole, specifically for the aforementioned bamboo species.

Content Analysis Result

Physical characterization (age, height, moisture content, grading properties)

Based on the reviewed sources, *Dendrocalamus asper* is the tallest bamboo (17.3 m). *Gigantochloa scortechinii* is 15.3 m shorter. *Gigantochloa levis* is the shortest, at 8.9 m. The three bamboo species have a wider error bar, indicating a faulty data distribution. Age and location affect bamboo height. Table 5 displays bamboo height at various ages. The researchers revealed that *Gigantochloa scortechinii* grows to 11.5 m, 12.3 m, and 13.9 m in age. Other bamboo investigations supported the conclusion (Wahab *et al*. 2010; Nordahlia *et al*. 2019). This shows that bamboo species height controls bamboo maturity. A four-year-old bamboo was reported at 25 m in Selangor, Malaysia, and 22.5 m in Bukidnon, Philippines. This shows that soil type impacted bamboo height. The average height of the three bamboo species varied greatly. *Dendrocalamus asper* had the thickest bamboo at 12.4 mm. This was followed by *Gigantochloa levis* (11.6 mm) and *Gigantochloa scortechinii* (8.1 mm). A low error bar for bamboo species is shown in Fig. 3a. This indicates that the data distribution is not precise. Location influenced bamboo thickness variation. *Dendrocalamus asper* is 16 mm thick in Selangor and 18.5 mm thick in Bukidnon. *Dendrocalamus asper* thickness was 11.5 mm at three years, 18.5 mm at four years, and 10.4 mm at seven years (Aguinsatan *et al*. 2019; Da Silva *et al*. 2019; Kadivar *et al*. 2019).

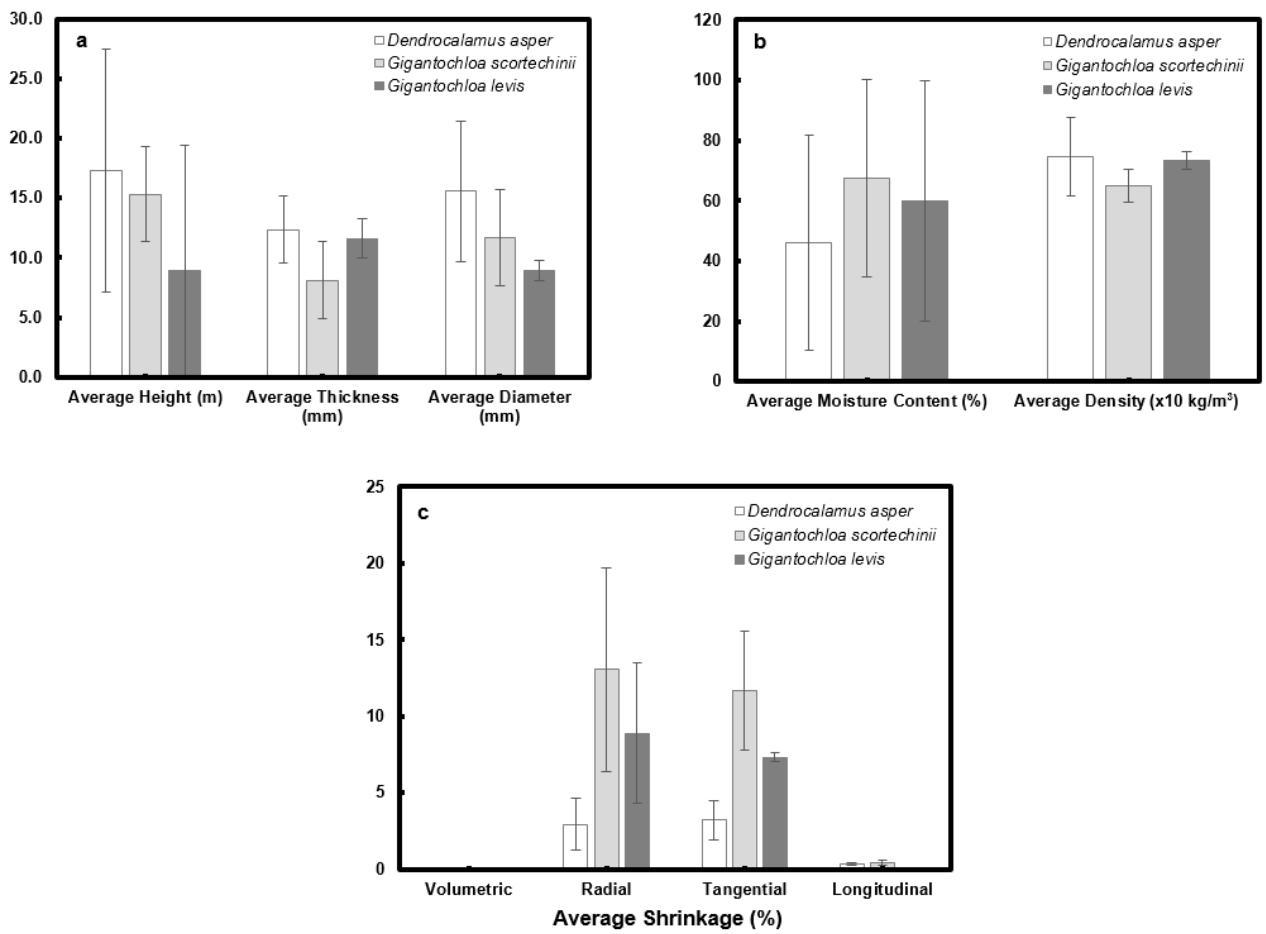

Fig. 3. Average of the physical characterization of three bamboo species

Table 5. Age, Height, Thickness, and Diameter of the Three Bamboo Species by Target Journals

Bamboo Species	Source	Location	Age (year)	Average Height (m)	Average Thickness (mm)	Average Diameter (cm)
Dendrocalamus asper	Rifqi *et al*. (2020)	Indonesia	-	-	10.0	11.0
	Handana *et al*. (2020)	Indonesia	-	-	8.5	30.0
	Damayanto *et al*. (2020)	Lombok, Indonesia	-	30.0	-	15.0
	Kadivar *et al*. (2019)	Pirassununga, Brazil	3	-	11.5	18.0
	Aguinsatan *et al*. (2019)	Bukidnon, Philippines	4	22.5	18.5	12.4
	Javadian *et al*. (2019)	Java island, Indonesia	-	15.0	13.0	15.0
	Awalluddin *et al*. (2019)	Malaysia	-	21.0	11.8	10.8
	Da Silva *et al*. (2019)	Brazil	7	-	10.4	11.9
	Nordahlia *et al*. (2019)	Selangor, Malaysia	4	20.0	16.0	-
	Yasin *et al*. (2018, 2019)	Yogyakarta, Indonesia	5	-	12.5	-
	Acma (2017)	Bukidnon, Philippines	4	-	-	20.0
	Srivaro *et al*. (2016)	Thailand	5	-	14.0	-
	Nordahlia *et al*. (2015)	Malaysia	4	25.0	9.5	18.0
	Azmy *et al*. (2009)	Selangor, Malaysia	1	2.20	-	-
			2	2.50	-	-
	Manalo *et al*. (2009)	Laguna, Philippine	2	-	-	9.0
Average				17.3	12.4	15.6
Standard deviation, s				10.1	2.8	5.9
Gigantochloa scortechinii	Salih *et al*. (2019)	Malaysia	4	-	6.0	-
	Awalluddin *et al*. (2019)	Malaysia	-	21.0	7.4	6.4
	Nordahlia *et al*. (2019)	Selangor, Malaysia	-	21.0	10.0	-
	Daud *et al*. (2018)	Selangor, Malaysia	3	-	18.6	5.3
	Mokhtar *et al*. (2018)	Kedah, Malaysia	-	20.0	8.0	10.0
	Wahab *et al*. (2015)	Selangor, Malaysia	3	-	-	17.0
	Mohamed *et al*. (2011)	Kedah, Malaysia	1	11.5	4.0	-
			2	12.3	5.0	-
			3	13.9	7.0	-
	Wahab *et al*. (2010)	Kedah, Malaysia	2	15.5	9.0	9.6
			4	15.5	9.0	9.3
	Asari *et al*. (2010)	Pahang, Malaysia	-	10.7	-	-
	Hamdan *et al*. (2009)	Selangor, Malaysia	4	12.0	-	15.0
	Hisham *et al*. (2006)	Kedah, Malaysia	0.5	-	8.0	14.8
			1.5	-	6.0	10.5
			3.5	-	7.7	11.5
			5.5	-	8.5	17.8
			6.5	-	6.5	16.0
	Wahab *et al*. (2005)	Kedah, Malaysia	4	-	9.0	9.0

Average				15.3	8.1	11.7
Standard deviation, s				4.0	3.2	4.0
Gigantochloa levis	Nordahlia *et al*. (2019)	Selangor, Malaysia	-	21.0	12.0	-
	Virtudazo *et al*. (2017)	Dumarao, Capiz, Philippines	3	-	9.8	10.0
	Wahab *et al*. (2016)	Kelantan, Malaysia	4	-	-	9.0
	Basari *et al*. (2015)	Lampung, Indonesia	4	-	13.0	8.6
	Razak *et al*. (2013)	Malaysia	3	-	-	8.0
	Azmy *et al*. (2009)	Selangor, Malaysia	1	2.2	-	-
			2	3.5	-	-
Average				8.9	11.6	8.9
Standard deviation, s				10.5	1.6	0.8

Note: (-) not covered by the previous studies

In general, age affects bamboo thickness. In this regard, *Gigantochloa levis* and *Gigantochloa scortechinii* displayed similar patterns of correlation between age and thickness. However, *Dendrocalamus asper* was the thickest bamboo among those three aforementioned species. Meanwhile, for the diameter, *Dendrocalamus asper* exhibited the most oversized average diameter of bamboo, which was 15.6 cm, among other species. Meanwhile, *Gigantochloa levis* indicated the least average bamboo diameter of 8.9 cm, and *Gigantochloa scortechinii* was placed in the second rank with 11.7 cm of the average bamboo diameter. Both *Dendrocalamus asper* and *Gigantochloa scortechinii* had a long error bar, which indicated less accuracy of the dataset distribution. Various studies show that the location affects bamboo diameter while age has no effect on bamboo diameter. Wahab *et al*. (2010) recorded 9.3 cm diameter for *Gigantochloa scortechinii* in Kedah, Malaysia, while Hamdan *et al*. (2009) claimed 15 cm diameter of same species in Selangor, Malaysia. At two and four years of bamboo age, Wahab *et al*. (2010) found that *Gigantochloa scortechinii* diameter decreased by 9.6 cm and 9.3 cm, respectively. However, Hisham *et al*. (2006) found that the diameter for that same species fluctuated as the age increased, as stipulated in Table 5. Comparatively, the bamboo diameter among those species was large.

Gigantochloa scortechinii has the highest average moisture content (67.51%) followed by *Gigantochloa levis* (59.94%). *Dendrocalamus asper* has the lowest average moisture content (46.01%). *Gigantochloa scortechinii* has a higher moisture content than other bamboo species. Figure 3b shows a longer standard deviation line. The data distribution and precision are vastly different. Bamboo's age and beginning moisture content alter moisture content. Hisham *et al*. (2006) studied bamboo moisture content over time and found that the bamboo loses moisture as they age in Table 6. At ages 0.5, 3.5, and 6.5, the water content was 90.5%, 65.40%, and 48.60%, respectively. They both have similar age-dependent moisture patterns (Razak *et al*. 2013; Wahab *et al*. 2016; Aguinsatan *et al*. 2019; Yasin *et al*. 2019). A decrease in moisture content was seen in green and air-dried samples. *Gigantochloa levis* green (65%) and air-dried (age 4) have 73.1% moisture. This pattern was seen in *Gigantochloa scortechinii* and *Dendrocalamus asper*. In other words, the beginning moisture content differential affects the final moisture content. These two variables are connected. *Dendrocalamus asper* and *Gigantochloa scortechinii* have reduced moisture content.

The *Dendrocalamus asper* bamboo has the highest average density at 747.5kg/m^3. However, *Gigantochloa scortechinii* has the lowest average density at 650.3kg/m^3. Three bamboo species have lower error bars. This shows a smooth, convergent data distribution. Bamboo density varies with age and moisture. Most studies revealed an age-density correlation. Table 6 indicates that bamboo density correlates with bamboo age. At 0.5, 3.5, and 6.5 years, *Gigantochloa scortechinii* density was 530, 610, and 680 kg/m^3, respectively. The age and density of *Dendrocalamus asper* were similar. Decreased densities of *Gigantochloa levis* with ageing were reported (Razak *et al*. 2013; Wahab *et al*. 2016). Location and environment can affect this. Bamboo's moisture content and density are linked. Due to its bulk, bamboo is low in moisture. *Gigantochloa scortechinii* and *Gigantochloa levis* shared a pattern. *Dendrocalamus asper* was 46.01% wet and 747.5 kg/m^3. *Gigantochloa levis* had a moisture content of 59.94% and a density of 734.3kg/m^3. The highest density and lowest moisture content bamboo is *Dendrocalamus asper*. *Gigantochloa levis* and *Gigantochloa scortechinii* had the highest bamboo density.

Table 6. Moisture Content, Density and Shrinkage of Bamboo

Bamboo Species	Source	Age (year)	Initial Moisture Content (%)	Average Moisture Content (%)	Average Density (kg/m³)	Average Shrinkage (%)			
						Volumetric	Radial	Tangential	Longitudinal
Dendrocalamus asper	Chiann *et al*. (2021)	3	12	33.17	920	-	0.90	1.47	-
	Marasigan *et al*. (2020)	4	-	-	780	-	-	-	-
	Rifqi *et al*. (2020)	-	-	33.12	990	-	-	-	-
	Nordahlia *et al*. (2019)	4	12	-	560	-	4.47	4.30	0.40
	Kadivar *et al*. (2019)	3	10.67	-	790	-	-	-	-
	Ismail *et al*. (2019)	4	-	86.83	660	-	-	-	-
	Aguinsatan *et al*. (2019)	4	16	93.55	-	8.45	4.25	4.05	0.30
	Javadian *et al*. (2019)	-	20	10.00	810	-	-	-	-
		-	45	13.30	-	-	-	-	-
	Da Silva *et al*. (2019)	7	-	-	730	-	-	-	-
	Yasin *et al*. (2018, 2019)	5	12	12.95	640	-	-	-	-
	Awalluddin *et al*. (2017)	-	-	18.63	-	-	-	-	-
	Srivaro *et al*. (2016)	5	12	-	800	-	2.18	3.08	-
	Nordahlia *et al*. (2015)	4	-	98.33	560	-	-	-	-
	Kamthai *et al*. (2005)	3	-	60.23	730	-	-	-	-
Average				46.01	747.5	-	2.95	3.23	0.35
Standard deviation, s				35.60	130.8	-	1.71	1.28	0.07
Gigantochloa scortechinii	Nordahlia *et al*. (2019)	4	12	-	640	-	-	-	-
	Mokhtar *et al*. (2018)	-	-	72.62	660	-	9.76	7.73	0.56
	Daud *et al*. (2018)	3	-	13.13	650	-	-	-	-
	Wahab *et al*. (2015)	3	-	109.18	710	16.83	8.72	11.74	-
	Awalluddin *et al*. (2017)	-	-	18.21	-	-	-	-	-
	Anokye *et al*.	4	-	86.16	690	-	-	-	-

	(2014a)								
	Jusoh *et al*. (2013)	-	12	-	700	-	-	-	-
	Wahab *et al*. (2012)	3	-	86.53	755	-	-	-	-
	Hamdan *et al*. (2009)	4	12	90.05	600	-	-	-	-
	Hisham *et al*. (2006)	0.5	-	90.50	530	-	-	-	-
		1.5	-	67.70	590	-	-	-	-
		3.5	-	65.40	610	-	-	-	-
		5.5	-	59.50	630	-	-	-	-
		6.5	-	48.60	680	-	-	-	-
	Anwar *et al*. (2005)	2	12	119.87	620	-	20.72	15.55	0.30
	Wahab *et al*. (2005)	4	65	72.62	660	-	-	-	-
		4	14	12.61	680	-	-	-	-
Average				67.51	650.3	-	13.07	11.7	0.43
Standard deviation, s				32.85	54.3	-	6.65	3.91	0.18
Gigantochloa levis	Nordahlia *et al*. (2019)	4	12	-	750	-	12.13	7.14	1.58
	Wahab *et al*. (2016)	4	65	73.10	685	-	-	-	-
		4	14	13.10	707	-	-	-	-
	Virtudazo *et al*. (2017)	3	-	23.50	-	-	-	-	-
	Basari *et al*. (2015)	4	-	103.83	765	-	-	-	-
	Razak *et al*. (2013)	3	-	86.18	750	11.08	5.67	7.52	-
	Nordahlia *et al*. (2012)	2	12	-	733	-	-	-	-
		4	12	-	750	-	-	-	-
Average				59.94	734.3	-	8.90	7.33	-
Standard deviation, s				39.72	28.5	-	4.57	0.27	-

Note: (-) not covered by the previous studies

As indicated in Fig. 3, *Gigantochloa scortechinii* and *Gigantochloa levis* shrinking averages are not shown because each bamboo species has only one journal. *Gigantochloa scortechinii* had the largest volumetric shrinkage (16.83%), whereas *Dendrocalamus asper* had the least (8.45%). There was a 11.18% volume loss in *Gigantochloa levis*. *Gigantochloa scortechinii* decreased 16.83% at 109.18% moisture, *Gigantochloa levis* shrank 11.08% at 86.18% moisture, and *Dendrocalamus asper* decreased 8.45% at 93.55% (Razak *et al*. 2013; Wahab *et al*. 2015; Aguinsatan *et al*. 2019). Shrinkage does not affect moisture content. But the evidence is imprecise and requires more examination. *Dendrocalamus asper* showed the lowest radial shrinkage (2.95%), *Gigantochloa scortechinii* has 13.07% and 8.90%. It also shows inadequate data dispersion for three bamboo species. Age affects data distribution. With respect to *Gigantochloa scortechinii* ageing, Wahab *et al*. (2015) and Anwar *et al*. (2005) show 2 and 3-year radial shrinkage. However, in age-related radial shrinkage, there was no data reported; neither for *Dendrocalamus asper* nor *Gigantochloa levis*. *Gigantochloa scortechinii* had the largest (11.7%) and lowest (*Dendrocalamus asper*) average tangential shrinkage (3.23%), while *Gigantochloa levis* shrank 7.33%. Its data distributions were convergent and precise, unlike *Dendrocalamus asper* and *Gigantochloa scortechinii*. *Gigantochloa scortechinii* shrank 8.72% tangentially and 16.83% voluminously. With respect to volumetric dehydration, the moisture content-radial shrinkage relationship in *Dendrocalamus asper*, *Gigantochloa levis* and *Gigantochloa scortechinii* is unknown. No data on *Gigantochloa levis* longitudinal shrinking was found. Both *Dendrocalamus asper* and *Gigantochloa scortechinii* shrank by 0.35% and 0.43% while between 2 and 4 years old, both species shrank by 0.3% (Anwar *et al*. 2005; Aguinsatan *et al*. 2019). Hence ageing had no effect on longitudinal shrinkage. Radial shrinkage trumped all others except *Dendrocalamus asper*, which shrank the most tangentially. *Gigantochloa scortechinii* had 13.07% and *Gigantochloa levis* had 8.90% radial shrinkage. In general, bamboo shrinks in two directions.

Mechanical characterization (shear, tensile, compression, and flexural)

Figure 4a shows the difference in shear strength of three bamboo species, including *Dendrocalamus asper*, *Gigantochloa scortechinii*, and *Gigantochloa levis*. 17 journals focused on the shear strength of three bamboo species, such as (Malanit *et al*. 2009; Yasin *et al*. 2018, 2019). The results from the previous studies are tabulated in Table 7. Based on the shear strength graph, the *Dendrocalamus asper* recorded the highest shear strength compared to other bamboos, 9.20 MPa. In contrast, *Gigantochloa scortechinii* recorded the lowest shear strength with 7.09 MPa. *Gigantochloa levis* appeared in middle-rank with 8.31MPa of shear strength. Comparing the shear strength between the bamboo species, the shear strength was approximately the same as each other. Significantly, the different data distribution of three bamboo species had a long error bar, which indicated that the values were more spread-out and less reliable. However, the difference in shear strength can be due to the initial condition of bamboo. Mokthtar *et al*. (2018) and Wahab *et al*. (2016) studied the shear strength of bamboo due to different initial conditions, which are green and air-dried. Mokhtar *et al*. (2018) found that the shear strength decreased from green to air-dried conditions for *Gigantochloa scortechinii* with 8.93MPa and 8.48MPa. Wahab *et al*. (2016) established this for *Gigantochloa levis*, but no journals covered the topic for *Dendrocalamus asper*.

Table 7. Shear Strength of Bamboo

Bamboo Species	Source	Age (year)	Condition	Average Shear Strength (MPa)
Dendrocalamus asper	Jesus *et al*. (2021)	-	-	7.36
	Awalluddin *et al*. (2020)	-	-	6.96
	Yasin *et al*. (2018, 2019)	5	-	7.55
	Srivaro *et al*. (2016)	5	-	12.88
	Malanit *et al*. (2009)	-	-	11.91
	Alipon *et al*. (2006)	-	-	8.52
Average				9.20
Standard deviation, s				2.55
Gigantochloa scortechinii	Awalluddin *et al*. (2020)	-	-	6.96
	Daud *et al*. (2018)	3	-	4.72
	Mokhtar *et al*. (2018); Wahab *et al*. (2005)	-	Green	8.93
		-	Dried	8.48
	Wahab *et al*. (2012, 2015)	3	Green	4.40
		3	Air-dried	9.03
Average				7.09
Standard deviation, s				2.10
Gigantochloa levis	Wahab *et al*. (2016)	4	65% (green)	9.20
		4	14% (dried)	8.80
	Virtudazo *et al*. (2017)	3	-	5.77
	Razak *et al*. (2013); Wahab *et al*. (2012)	3	Green	8.38
		3	Air-dried	9.38
Average				8.31
Standard deviation, s				1.47

Note: (-) not covered by the previous studies

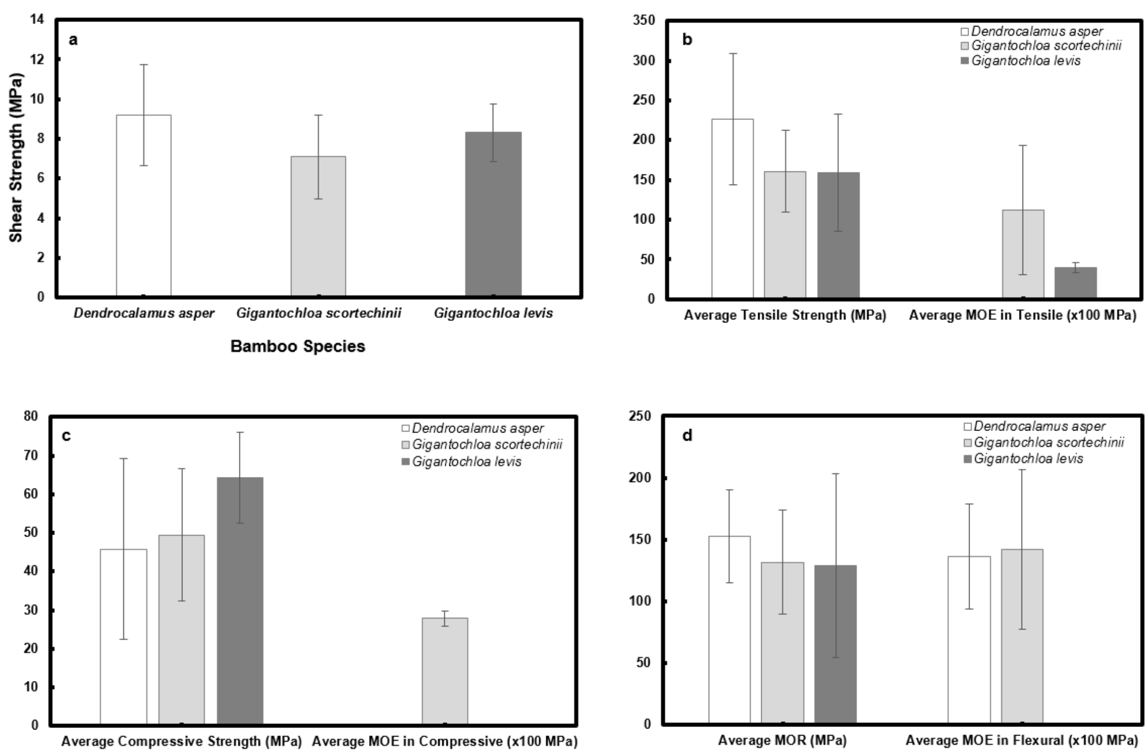

Fig. 4. Average shear, tensile, compressive, flexural strength of bamboo from various bamboo species

Figure 4b shows the difference in average tensile strength and MOE of three bamboo species, including *Dendrocalamus asper*, *Gigantochloa scortechinii*, and *Gigantochloa levis*. Twenty journals focused on the tensile strength and modulus of elastic (MOE) in tensile of three bamboo species, such as Javadian *et al*. (2019), Jais *et al*. (2020) and Rifqi *et al*. (2020). Based on the tensile strength graph, the *Dendrocalamus asper* recorded the highest average tensile strength compared to other bamboo, 226.20 MPa. In contrast, *Gigantochloa levis* recorded the lowest tensile strength with 159.14 MPa. *Gigantochloa scortechinii* recorded slightly higher than *Gigantochloa levis*, which is 160.94 MPa of average tensile strength. The error bar indicates that the data distribution is relatively high between the samples, which are divergent and not precise. The different data of *Gigantochloa scortechinii* and *Gigantochloa levis* can be due to initial moisture content. Razak *et al*. (2013) and Wahab *et al*. (2015) showed increasing tensile strength from green to air-dried condition for *Gigantochloa scortechinii* and *Gigantochloa levis* in Table 8. This shows that the higher the moisture content, the lower the tensile strength. Researchers need to extend the studies in tensile strength of this bamboo species to have more accurate data. From Table 8, the correlation of tensile strength and bamboo age cannot be proven, as there has been a lack of studies focused on tensile strength based on age.

Based on the MOE in the tensile graph (Fig. 4b), *Gigantochloa levis* is recorded as having the lowest average MOE, with 3976 MPa. *Gigantochloa scortechinii* indicated the highest average MOE, which is 11210.5 MPa. The line of standard deviation was longer for *Gigantochloa scortechinii* and shorter for *Gigantochloa levis*. This shows that the data between the journals for *Gigantochloa scortechinii* was divergent and not precise, unlike *Gigantochloa levis*. The difference of modulus of tensile can be due to the initial condition of bamboo. Razak *et al*. (2013) and Wahab *et al*. (2015) showed increasing modulus in tensile from green to air-dried condition for *Gigantochloa scortechinii* and *Gigantochloa levis*. This shows that the initial moisture content influenced the modulus of tensile. No average tensile strength was recorded for *Dendrocalamus asper*, as there had been a lack of research in this context. However, Javadian *et al*. (2019) recorded the MOE for *Dendrocalamus asper*, which is 21858 MPa. From Table 8, the correlation of MOE in tensile and bamboo age cannot be proven, as there has been a lack of studies focused on MOE based on age. However, the MOE of *Gigantochloa scortechinii* was recorded as being higher than *Gigantochloa levis*, although the tensile strength of *Gigantochloa scortechinii* was lower than *Gigantochloa levis*. This shows that the *Gigantochloa levis* indicated lower resistance to being deformed elastically after being pulled compared to *Gigantochloa scortechinii*, but this cannot be demonstrated fully, as no researchers focused on the MOE in the tensile mode.

Figure 4c shows the difference in average compressive strength of three bamboo species, including *Dendrocalamus asper*, *Gigantochloa scortechinii*, and *Gigantochloa levis*. Twenty-four journals focused on the compressive strength of three bamboo species, such as Malanit *et al*. (2009) and Yasin *et al*. (2018). Based on the compressive strength graph, the *Gigantochloa levis* recorded the highest average compressive strength compared to other bamboo, 64.27 MPa. In contrast, *Dendrocalamus asper* recorded the lowest average compressive strength with 45.77 MPa. *Gigantochloa scortechinii* appeared in the middle rank with 49.40 MPa of average compressive strength. The data distribution of three bamboo species was quite high, as illustrated in error bar. The difference in compressive strength can be due to the initial condition of bamboo. Mokhtar *et al*. (2018) and Wahab *et al*. (2016) studied the compressive strength of bamboo due to different initial conditions, which are green and air-dried. Mokhtar *et al*. (2018) found that the compressive strength increased from green to air-dried conditions for *Gigantochloa scortechinii* with 53.35 MPa and 61.9 MPa. Wahab *et al*. (2016) demonstrated this for *Gigantochloa levis*, but no journals covered the topic for *Dendrocalamus asper*.

Table 8. Tensile Strength and MOE of Bamboo

Bamboo Species	Source	Age (year)	Condition	Average Tensile Strength (MPa)	Average MOE (MPa)
Dendrocalamus asper	Jesus *et al*. (2021)	-	-	307.89	-
	Handana *et al*. (2020)	-	-	142.88	-
	Rifqi *et al*. (2020)	-	-	284.69	-
	Awalluddin *et al*. (2020)	-	-	210.70	-
	Javadian *et al*. (2019)	-	-	282.18	21858
	Da Silva *et al*. (2019)	7	-	84.04	-
	Yasin *et al*. (2018, 2019)	5	-	330.93	-
	Awalluddin *et al*. (2017)	-	-	221.96	-
	Srivaro *et al*. (2016)	5	-	170.50	-
Average				226.20	-
Standard deviation, s				82.70	-
Gigantochloa scortechinii	Awalluddin *et al*. (2020)	-	-	157.54	-
	Jais *et al*. (2020)	4	-	183.51	-
	Salih *et al*. (2019)	4	-	182.33	17300
	Zakikhani *et al*. (2017)	-	-	245.67	21465
	Awalluddin *et al*. (2017)	-	-	169.60	-
	Wahab *et al*. (2012, 2015)	3	Green	78.63	2118
		3	Air-dried	165.68	4795
	Bahari *et al*. (2010b)	3	-	104.54	10375
Average				160.94	11210.5
Standard deviation, s				51.01	8166.6
Gigantochloa levis	Jais *et al*. (2020)	4	-	242.81	-
	Razak *et al*. (2013)	3	Green	103.09	3552
		3	Air-dried	131.53	4400
Average				159.14	3976.0
Standard deviation, s				73.84	599.6

Note: (-) not covered by the previous studies

The average MOE in compression was recorded only for *Gigantochloa scortechinii*, with 2781.2 MPa. The error bar was shorter. This shows that the data distribution of *Gigantochloa levis* was accurate and converged. However, no data recorded for *Dendrocalamus asper* and *Gigantochloa levis*. Hence, *Gigantochloa levis* has good compressive strength compared to *Gigantochloa scortechinii* and *Dendrocalamus asper*. In the majority, the compressive strength showed an increased pattern from green to air-dried conditions.

Table 9. Compressive Strength of Bamboo

Bamboo Species	Source	Age (year)	Condition	Average Compressive Strength (MPa)	Average Moe (MPa)
Dendrocalamus asper	Jesus *et al*. (2021)	-	-	47.25	-
	Handana *et al*. (2020)	-	-	50.31	-
	Rifqi *et al*. (2020)	-	-	38.42	-
	Awalluddin *et al*. (2019)	-	-	33.78	-
	Ismail and Adam (2019)	4	-	55.83	-
	Yasin *et al*. (2018, 2019)	5	-	23.52	-
	Acma (2017)	4	-	104.02	-
	Awalluddin *et al*. (2017)	-	-	58.15	-
	Amatosa *et al*. (2016)	2	-	34.12	-
	Malanit *et al*. (2009)	-	-	14.39	-
	Alipon *et al*. (2006)	2	-	43.73	-
Average				45.77	-
Standard deviation, s				23.43	-
Gigantochloa scortechinii	Awalluddin *et al*. (2019)	-	-	20.03	-
	Daud *et al*. (2018)	3	-	22.33	-
	Mokhtar *et al*. (2018); Wahab *et al*. (2005)	-	Green	53.35	-
		-	Dried	61.90	-
	Awalluddin *et al*. (2017)	-	-	58.15	-
	Jusoh *et al*. (2013)	-	Skin	45.74	2912
		-	Unskin	43.50	2650
	Wahab *et al*. (2006); Razak *et al*. (2006)	2	-	54.13	-
		4	-	59.76	-
	Hamdan *et al*. (2009)	4	Green	33.07	-
		-	Air-dried	75.34	-
	Anwar *et al*. (2005)	2	-	65.55	-
Average				49.40	2781.2
Standard deviation, s				17.11	185.6
Gigantochloa levis	Virtudazo *et al*. (2017)	3		77.02	-
			65% (green)	53.70	-
	Wahab *et al*. (2016)	4	14% (dried)	62.10	-
Average				64.27	-
Standard deviation, s				11.81	-

Note: (-) not covered by the previous studies

Figure 4d shows the average flexural strength and modulus of elasticity (MOE) of three bamboo species, including *Dendrocalamus asper*, *Gigantochloa scortechinii*, and *Gigantochloa levis*. Twenty-eight journals focused on flexural strength (MOR) and MOE in flexural of three bamboo species. Based on the flexural strength graph, the *Gigantochloa levis* recorded the lowest average flexural strength compared to other bamboo, 128.7 MPa. In contrast, *D. asper* recorded the highest average flexural strength with 152.7 MPa. *Gigantochloa scortechinii* recorded slightly higher than *G. levis*, which is 131.7 MPa of average flexural strength. The error bar shows higher differences in data distribution. This shows that the results were not precise. The higher flexural strength in *G. levis* due to data collected by Virtudazo *et al*. (2017) is much lower than Wahab *et al*. (2016), which is 43.4 and 180 MPa at ages 3 and 4, respectively, in Table 10. Hence, more researchers need to study flexural strength of bamboo to get the approximate value for *G. levis*. Based on the

MOE in the flexural graph (Fig. 4d), *G. scortechinii* recorded the highest average MOE in flexural with 14199.1 MPa, and *D. asper* indicated 13627.5 MPa of average MOE in flexural mode. The data distribution was also judged to be not reliable, as there was too much difference between the articles in different journals. Nordahlia *et al*. (2019) found that *G. levis* recorded 13185 MPa of flexural modulus. Hence, *D. asper* has good flexural strength compared to *G. scortechinii* and *G. levis*. However, the MOE in flexural mode of *G. scortechinii* recorded higher MOE than *D. asper*. More data are required to get accurate flexural strength and flexural modulus readings for these three bamboo species.

Table 10. Flexural Strength and MOE of Bamboo

Bamboo Species	Source	Age (year)	Condition	Average Flexural Strength (MOR) (MPa)	Average MOE (MPa)
Dendrocalamus asper	Chiann *et al*. (2021)	3	-	119.9	12262
	Ismail *et al*. (2019)	4	-	180.0	7755
	Kadivar *et al*. (2019)	3	-	203.5	19623
	Aguinsatan *et al*. (2019)	4	-	121.5	10800
	Javadian *et al*. (2019)	-	-	162.3	12075
	Yasin *et al*. (2018, 2019)	5	-	152.1	17960
	Nordahlia *et al*. (2015, 2019)	4	-	150.3	11303
	Srivaro *et al*. (2016)	5	-	160.0	19161
	Amatosa *et al*. (2016)	2	-	71.8	7600
	Malanit *et al*. (2009)	-	-	198.5	15363
	Manalo *et al*. (2009)	2	-	160.0	16000
Average				152.7	13627.5
Standard deviation, s				37.7	4271.6
Gigantochloa scortechinii	Salih *et al*. (2019)	4	-	196.7	11460
	Daud *et al*. (2018)	3	-	59.0	27480
	Nordahlia *et al*. (2015, 2019)	4	-	125.0	10039
	Wahab *et al*. (2005); Mokhtar *et al*. (2018)	-	Green	158.0	16989
		-	Dried	174.0	18582
	Wahab *et al*. (2006); Razak *et al*. (2006)	2	-	133.7	-
		4	-	139.0	-
	Bahari *et al*. (2010a)	3	-	77.2	5853
	Hamdan *et al*. (2009)	4	Green	88.0	8552
		4	Air-dried	140.7	13057
	Anwar *et al*. (2005)	2	-	157.4	15780
Average				131.7	14199.1
Standard deviation, s				42.1	6456.9
Gigantochloa levis	Nordahlia *et al*. (2015, 2019)	4	-	162.7	13185
	Virtudazo *et al*. (2017)	3	-	43.4	-
	Wahab *et al*. (2016)	4	-	180.0	-
Average				128.7	-
Standard deviation, s				74.4	-

Note: (-) not covered by the previous studies

Table 11. Failure Mechanism of Bamboo Species

Source	Bamboo Species			Compression Test			Tensile Test								Shear Test			Bending Test		
	Dendrocalamus asper	*Gigantochloa scortechinii*	*Gigantochloa levis*	End bearing	Buckling	splitting	At reduced area	Along specimen grip	At interface of grip and gage length	Along the gauge length	Single split	Tension and shear parallel to grain	Brooming	Splintering	Cracks	Split	Fracture surface	Longitudinal splitting	Transverse failure	Face fracture
Handana *et al*. (2020)	✓			✓		✓	✓													
Awalluddin *et al*. (2020)	✓	✓						✓	✓	✓	✓		✓		✓					
Awalluddin *et al*. (2019)	✓	✓			✓	✓														
Daud *et al*. (2018)		✓		✓		✓										✓		✓		
Awalluddin *et al*. (2017)	✓	✓		✓		✓						✓								
Srivaro and Jakranod (2016)	✓								✓								✓			✓
Bahari *et al*. (2010b)		✓												✓						
Hamdan *et al*. (2009)		✓		✓		✓												✓	✓	
Hamdan and Breese (2007)						✓														

Note: (✓) covered by the previous studies

Failure mechanism

When pressure from compression, bending, shear, and bending tests were developed, it has been reported that different bamboo species fail by different mechanisms. Table 11 shows end bearing, buckling, vertical crack, and splitting in bamboo species. A crack pattern at the top section high thickness wall only failed in end bearing for *Gigantochloa scortechinii*, according to Handana *et al*. (2020). Meanwhile, buckling behavior was exhibited in *Dendrocalamus asper* and *Gigantochloa scortechinii* (Awalluddin *et al*. 2019). In *D. asper* and *G. scortechinii*, vertical cracks or splits were detected. Daud *et al*. (2018) stated that internode specimens have vertical cracks. This indicated that both bamboo species failed the compressive test. Previous research found failure at the decreased area, specimen grip, interface of grip, and gauge length, along the gauge length, single split, tension, and shear parallel to grain and brooming. Awalluddin *et al*. (2017) and Handana *et al*. (2020) revealed bamboo failure at reduced area and tension and shear parallel to the grain for *D. asper* and *G. scortechinii*, respectively. Previous researchers have observed three failures, cracks, and splits in the shear test. Daud *et al*. (2018) claimed that internode bamboo was weak and splittable. *Dendrocalamus asper* and *G. scortechinii* were observed to have cracked surfaces (Hamdan *et al*. 2009; Awalluddin *et al*. 2020). Hamdan *et al*. (2009) discovered transverse and longitudinal splitting in internode. End bearing and splitting were observed in both *D. asper* and *G. scortechinii* tests. However, the failure mechanism in *G. levis* is yet to be concluded.

Discussion

To evaluate bamboo qualities, one must consider how physical properties affect mechanical properties. The average tensile strength of the three bamboo species has been reported to vary with moisture content and density. *Dendrocalamus asper* had the highest average tensile strength, density, and moisture content (226.2 MPa, 747.5 kg/m^3, and 46.01%). *Gigantochloa scortechinii*'s tensile strength was 160.9 MPa, but its moisture content was 67.5%, and its density was 650 kg/m^3, while *G. levis* had the lowest average tensile strength of 159.1 MPa, with 59.9% moisture content and 734 kg/m^3 density. The physical qualities of bamboo influenced the average tensile modulus, with *G. levis* having the lowest average tensile modulus, 3976 MPa, and having the average density of 734.3 kg/m^3. *Gigantochloa scortechinii* had the highest average tensile modulus, 11210 MPa, and the lowest average density, 650 kg/m^3. The tensile modulus linked with bamboo physical characteristics. No data exists for *D. asper* to support this pattern. The journal has very distinct data distribution for tensile strength and tensile modulus. For the three bamboo species, more research is required.

Since the results of the compressive strength reported is very limited, it is impossible to identify the correlation between the physical characterization (moisture content and density) and the compressive strength of bamboo. This needs further study for a better overview. Nevertheless, *D. asper* had the lowest average compressive strength of 45.77 MPa and the lowest average moisture content of 46.01%. *Gigantochloa scortechinii*, with 67.51% average moisture content and 650.3kg/m^3 average density, had the second greatest average compressive strength of 49.4 MPa. *Gigantochloa levis* had the highest average compressive strength of 64.27 MPa, 59.94% average moisture content, and 734.3 kg/m^3 average density. Previous research only included *G. scortechinii*, which has a compressive modulus of 2781 MPa. The error bar shows a moderate data distribution amongst studies, indicating a lack of precision.

Table 12. Consolidation of Average Moisture Content, Density, and Mechanical Properties of Bamboo Species

Bamboo Species	Average Moisture Content (%)	Average Density (kg/m^3)	Average Tensile Strength (MPa)	Average Tensile Modulus (MPa)	Average Compressive Strength (MPa)	Average Compressive Modulus (MPa)	Average Flexural Strength (MPa)	Average Flexural Modulus (MPa)	Average Shear Strength (MPa)
Dendrocalamus asper	46.01	747.5	226.2	-	45.77	-	152.72	13627.5	9.2
Gigantochloa scortechinii	67.51	650.3	160.94	11210.5	49.4	2781.2	131.69	14199.1	7.09
Gigantochloa levis	59.94	734.3	159.14	3976	64.27	-	128.67	-	8.31

Note: (-) not covered by the previous studies

Table 13. Consolidation of All Mechanical Properties from Previous Studies

Bamboo Species	Tensile Strength (MPa)	Tensile Modulus (MPa)	Compressive Strength (MPa)	Compressive Modulus (MPa)	Flexural Strength (MPa)	Flexural Modulus (MPa)	Shear Strength (MPa)
Dendrocalamus asper	84.04 - 330.93	-	14.39 - 104.02	-	71.8 - 203.5	7600 - 19623	6.96 - 12.88
Gigantochloa scortechinii	78.63 - 245.67	2118 - 21465	20.03 - 75.34	2650 - 2912	59.0 - 196.7	5853 - 27480	4.4 - 9.03
Gigantochloa levis	103.9 - 242.81	3552 - 4400	53.70 - 77.02	-	43.4 - 180.0	-	5.77 - 9.38

Note: (-) not covered by the previous studies

Dendrocalamus asper had the highest average flexural strength and density at 46.01%, 747.5 kg/m^3, and 152.72 MPa. However, in *G. scortechinii* and *G. levis*, the moisture content and density did not correlate with flexural strength. However, it had the highest average moisture content (67.51%) and the lowest density (650.3 kg/m^3). *Gigantochloa levis* had the lowest average flexural strength (128.7 MPa) and density (734.3 kg/m^3). *Gigantochloa scortechinii* had the highest average flexural modulus, 14200 MPa, at 67.51% moisture content, and the lowest average density, 650.3 kg/m^3. Despite having the lowest average moisture content and highest average density, *D. asper* has the lowest average flexural strength, 13630 MPa. No research has been done on *G. levis* to prove this pattern. However, the error bar shows a longer standard deviation line, indicating a skewed data distribution.

Shear strength is inversely proportional to average moisture content and directly related to average density of *D. asper*, *G. scortechinii*, and *G. levis*. The lower the moisture content, the higher the shear strength. The shear strength of bamboo increases with density, 9.2 MPa, 747. 5kg/m^3, and 46.01% for *D. asper*. *Gigantochloa scortechinii* and *G. levis* had similar patterns. Average shear strength was 7.09 MPa for *G. scortechinii* at 67.51% average moisture content and 650.3 kg/m^3 average density. The error bar shows the standard deviation. This indicated that the shear strength data distribution was precise. Shear strength of three bamboo species increased with lower moisture content and density. However, no investigations have been done on the shear modulus of bamboo. Table 12 summarizes the effect of moisture content and density on mechanical properties, while Table 13 summarizes all mechanical properties from the existing literature.

CONCLUSIONS

This study examined the mechanical characterization of three species of bamboo poles. The selected research articles make it possible to summarize the mechanical properties of bamboo poles, based on various study disciplines. *Dendrocalamus asper* has higher average bamboo height, thickness, diameter, and density than *Gigantochloa scortechinii* and *Gigantochloa levis,* but lower average moisture content than the latter. For bamboo density, *G. levis* ranked second, followed by *G. scortechinii*. Due to a paucity of research, the correlation between the shrinkage characterization and mechanical characterization cannot be directly determined. *Dendrocalamus asper* showed the least tangential, radial, and longitudinal shrinkage while possessing higher shear, tensile, and flexural strength than *G. scortechinii* and *G. levis*.

Generally, shear strength decreased from green to air-dried condition. Like *G. scortechinii* and *D. asper*, both species possess good compressive strength. Tensile and flexural modulus were highest in *G. scortechinii*, while compressive modulus was highest in *G. levis*. There was no data found for *D. asper* tensile and compression modulus. End bearing and splitting were observed in both *D. asper* and *G. scortechinii* tests. However, no one knows how *G. levis* fails. A bamboo’s shear strength varies inversely with moisture content and directly with density. Conversely, *G. levis* had the lowest tensile modulus at the lowest moisture level and maximum density. However, the results showed that the moisture content and density of bamboo had no effect on compressive, tensile, and flexural strength values. Previous research only covered *G. scortechinii*; hence the impact of compressive modulus on bamboo characteristics is unknown. Except for compressive strength, moisture content and density have been reported to alter bamboo’s mechanical properties. The data distribution of the three species was high. This suggested that earlier reported data for differences between research samples were unreliable and misleading. The localization, age, and initial moisture content of bamboo are factors underlying the differences. Based on the tensile strength of the bamboo, its properties are analogous to those of steel, which likewise has higher tensile than compressive strength. The data dispersion of bamboo species physical and mechanical characterization was high due to a lack of bamboo research. More research is needed to evaluate bamboo qualities to gain precise data, especially regarding the constitution of ISO 22157:2019 and will contribute to a body of knowledge of bamboo's material performance for building and construction domain.

In summary, bamboo is widely known for its exceptional mechanical strength, which makes it a highly desirable material for a variety of applications. Its strength-to-weight ratio is superior to that of many other materials, including steel and timber. Bamboo culms are highly flexible and resilient, making them an ideal building material for structures that require a high degree of flexibility to withstand wind and seismic loads. Additionally, the natural antibacterial and fungal properties of bamboo make it an excellent material for use in humid and damp environments. Overall, bamboo's exceptional mechanical strength, ecological sustainability, and versatility make it an excellent choice for a wide range of applications, from construction and furniture to textiles and even electronics.

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Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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