Journal of Renewable Materials

Tech Science Press

DOI: 10.32604/jrm.2021.014109

ARTICLE

Dynamic Changes of Chemical and Mechanical Properties of Moso Bamboo (*Phyllostachys edulis*) Culms under Different Storage Conditions

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Received: 31 August 2020 Accepted: 19 October 2020

ABSTRACT

The durability of bamboo based on its chemical and mechanical properties is a crucial consideration for the wood-based industry due to its vulnerability to insects and microorganisms. We investigated the dynamic changes of chemical and mechanical properties of *Phyllostachys edulis* under air-dry and water storage conditions for 3, 6 and 12 months respectively. The chemical properties of *P. edulis* bamboo culms varied with culm age but insignificantly with culm height. The mechanical properties of *P. edulis* culms showed an increasing trend with culm age. Water storage condition decreased the ash, SiO_2 and lignin content, but increased the ethanol-benzene extracts. It also created an anaerobic environment for bamboo culms in which only anaerobic respiration was possible contributing to reducing the content of soluble sugar and starch, thereby beneficial for decreasing the damage from insects and microorganisms. Moreover, the water storage conditions could maintain culm mechanical performance better. Therefore, the indigenous practice of local people to store bamboo culms in ponds has good science behind it and water storage practices of bamboo culms was recommended.

KEYWORDS

Phyllostachys edulis; chemical properties; mechanical properties; storage conditions

1 Introduction

Bamboo has become the most important non-wood material for the wood-based industry due to its easy propagation, fast growth and high productivity [1]. Bamboo use is wide-ranging from construction and reinforcing fibers, paper, textiles and boards, food and combustion and bioenergy applications [2]. The chemical and mechanical properties of bamboo timber are fundamental for its utilization as they affect the processing procedures and the performance of end products significantly [1]. Similar to the ratios reported in both softwood and hardwood, bamboo contains 40%–48% cellulose, 22%–27% hemicellulose and 25%–30% lignin, enhancing the mechanical properties of bamboo [2]. With such compressive, tensile and bending strengths equivalent to those of wood and steel commonly used for scaffolding, bamboo exhibits excellent compression and bending properties [3]. Furthermore, bamboo is widely used in light-frame buildings nowadays due to its better dimensional stability [4,5], larger axial tension and compression strength [4,6] as well as comparable thermal insulation performances compared to wood [7]. However, for industry use, especially in architectural application, the durability of bamboo is a crucial consideration due to its vulnerability to insects and microorganisms [8]. Low durability of bamboo is associated strongly with its chemical composition of high sugar and starch content, making it susceptible to mold, fungal infection and insect attack [9]. The durability of raw bamboo varies by species, age and preservation techniques [10]. In good storage or use conditions, raw bamboo is estimated to have a design life of 10–15 years [10]. In order to improve its properties, bamboo are commonly treated with preservatives used for wood, however, these preservatives have posed adverse influence on human health and environment [9].

In the vast rural areas of south of China, it is often not possible to transport bamboo culms to factories in time for processing and utilization after being logged. They are air-dried *in situ* temporarily but are susceptible to mold and fungal attack because of the high humidity environment. The traditional method of storing logs in local pond water to prevent wood borers and fungi is practiced. Researchers have conducted some related works based on this method on wood [11]. However, research on such storage practices of bamboo culms is rare. The chemical and mechanical properties of bamboo after water storage have not yet been fully studied and whether water storage is suitable for bamboo is yet to be explored.

Moso bamboo (*Phyllostachys edulis*) is most extensively distributed and cultivated in China and is widely used in construction materials, handicraft, pulp and paper, biomass energy, etc. In this study, we explored the dynamic changes of the chemical and mechanical properties, as well as the soluble sugar and starch contents of *P. edulis* culms after storing in pond water for 3, 6 and 12 months in comparison with the air dried culms. Our work could provide theoretical basis and references for the large-scale industrial processing and utilization of bamboo resources.

2 Materials and Methods

2.1 Materials and Treatment

P. edulis bamboo culms were obtained from Xiangyin county of Yueyang City, Hunan Province of China (28°33′38″N, 112°48′44″E; Altitude: 81 m) in December, 2017, with the local annual mean temperature at 16.5°C (highest at 29°C in July and lowest at 5°C in January) and annual mean relative humidity at 79% (highest 84% in September and lowest 78% in July), respectively. 21 culms of moso bamboos in each of the three age class (1, 2, and 3 years old), totaling 63 culms, were cut. Internodes of each culm were consecutively numbered from the bottom to the top and were then divided into three portions, each with an equal number of internodes, i.e., 1^{st} for bottom, 11^{th} for middle and 22^{nd} for top portion.

The control groups of 9 culms (3 culms in each of the 3 age groups) were used to analyze the chemical and mechanical properties, and the soluble sugar and starch contents. For analytical comparison, 27 culms (3 culms in each of the three age groups from three drying periods) were exposed for drying under natural climatic conditions (3, 6 and 12 months) and the rest 27 culms of three age groups were stored in pond water for the same time periods.

2.2 Methods

2.2.1 Determination of Chemical Properties

We oven-dried the internode strips at 60°C for 24 h and ground in a Wiley mill (FW100, China). Milled material passing a 40-mesh sieve but retaining on 60 mesh screen was used for chemical analyses, which were carried out in compliance with the Chinese National Standards for Testing and Materials. We carbonized the milled samples in a porcelain crucible on an electric stove and then in a muffle furnace at 575 ± 25°C for 2 h. Ash samples were then taken out, cooled to room temperature and weighted (Ash-GB/T 2677.3-93). And then, we added 5 mL of 6 mol/liter HCl which was evaporated in a steam bath. Based on three repetitions, distilled water was used to rinse the residue which was then filtered, and moved to the same muffle furnace and heated at 575 ± 25°C for 2 h and SiO_2 weight was obtained

(SiO_2-GB/T7978). We packaged the milled samples using filter paper and loaded them in a Soxhlet extractor. Benzene alcohol solution (2:l) was applied for 6 h water-bath extraction and the extracts were weighed (Toluene–alcohol extractives-GB/T10741-89). The residue was unpackaged and moved into a conical flask for 2 h water-bath with 15 mL of sulfuric acid (72%). Then, we added distilled water to 560 mL, and after 4 h water-bath, we filtered the solution, rinsed the residue using distilled water, which was dried and weighed to determine acid-insoluble lignin content. Filtrate of the acid-insoluble lignin was metered by ultraviolet spectrophotometer (752 N Hengping) under the absorbance at 205 nm to be acid-soluble lignin (Lignin-GB/T 2677.8-94, GB/T 10337-2008). After 6 h water-bath for extraction, samples were loaded into a conical flask, and mixed with 65 mL distilled water, 0.5 mL acetic acid, and 0.75 g sodium chlorite. After 1 h water-bath at the constant temperature 75°C, and then mixed with 0.5 mL acetic acid and 0.75 g sodium chlorite. We obtained whitish materials after four repeated procedures. Filtering and rinsing with distilled water was practiced until filtrate from the solution presented no acidity. Lastly, we washed the residue 3 times using acetone, dried and holocellulose weight was obtained (Holocellulose-GB/T 2677.10-1995). Each test was triplicated.

2.2.2 Determination of Soluble Sugar and Starch Content

We determined the soluble sugar and starch contents using the phenol-sulfuric acid method [8]. Samples (0.2 g) were powdered in a mortar and pestle with liquid nitrogen, and then extracted with distilled water. The supernatants centrifugally collected at 6,000 rpm for 15 min, were mixed with 5% phenol and 98% sulfuric acid for 1 h. We used a spectrophotometer (752 N Hengping) to determine absorbance at 485 nm. The sediments were collected and used to determine the starch contents. Each test was triplicated.

2.2.3 Determination of Mechanical Properties

The samples for mechanical properties were derived from internodes 11 (middle portions of the culms), which were usually one of the longest internodes of the culms. These internodes were stored in a conditioning room maintained at 23°C and 65% relative humidity until moisture content (12%) was achieved. The procedures used for the determination of mechanical properties (compressing strength, tensile strength and bending strength) were conducted according to the Chinese National Standards for Testing Methods for Physical and Mechanical properties of bamboo (GB/T 15780-1995). Each test was triplicated.

3 Results and Discussion

3.1 Variation of Chemical Compositions under Different Storage Conditions

The average chemical compositions of the *P. edulis* culms control varied with age but insignificantly with culm heights (Tab. 1). Ash content decreased with culm age, with 1- and 2-year culms containing significantly higher ash content than that of 3-year culms. SiO_2 content showed a downward and then upward trend, and reached its highest value at the 3rd year. The ethanol-benzene extract, lignin and holocellulose content slightly increased with age (Tab. 1).

Under the air-dry condition, the average ash content of *P. edulis* culms showed increasing trend as compared to the control. It reached the highest value (2.27%) in the 6th month, but declined to the lowest (1.66%) in the 12th month. While under the water storage condition, the ash content declined to 0.96% in the 3rd month, significantly lower than those of the control and the air-dry ones, and it continued to decrease with storage time to 0.71% in the 12th month (Fig. 1). The mean ash content of *P. edulis* culms under the water storage condition was apparently lower than that under the air-dry condition as well as the control. Lower ash content indicates high pulp yield from pulping process [12] and help reduce the risks of environmental pollution to some extent. Moreover, high ash content for some bamboo species can adversely affect tool/knife wear during machining operations [13]. Therefore, the *P. edulis* culms stored in water for a period with lower ash content would benefit industry processing.

Table 1: Chemical compositions of *Phyllostachys edulis* culms under different storage conditions (%)

Storage condition	Position	Age class	Ash	SiO_2	Ethanol–benzene extracts	Lignin			Holocellulose
						Acid-soluble	Acid-insoluble	Lignin	
Control		I	1.83A	0.28AB	4.59A	2.61A	29.42A	32.03A	65.97A
		II	1.68A	0.21B	4.62A	2.82A	29.27A	32.09A	67.24A
		III	0.98B	0.36A	5.11A	2.81A	28.62A	30.48A	66.59A
	Top		1.36a	0.23a	4.58a	2.76a	28.27a	31.01b	67.69a
	Middle		1.72a	0.33a	4.88a	2.83a	30.09a	32.92a	66.34a
	Bottom		1.42a	0.29a	4.85a	2.67a	28.94a	30.67b	65.77a
3M Water stored		I	1.12A	0.28A	0.80B	2.08A	25.60A	27.68A	67.93A
		II	1.17A	0.34A	2.05A	1.78B	24.29A	26.07A	66.68A
		III	0.59B	0.34A	1.89A	2.15AB	24.84A	26.99A	69.49A
	Top		0.94a	0.41a	2.05a	1.95a	23.90a	25.85a	67.60a
	Middle		1.25a	0.27a	1.85a	2.00a	26.10a	28.10a	69.95a
	Bottom		0.68a	0.27a	1.73a	2.07a	24.72a	26.79a	66.55a
3M Air dried		I	2.77A	0.46B	1.37B	1.88B	19.42B	21.30B	65.97A
		II	1.70B	0.28B	2.05A	2.43A	22.70A	25.13A	67.21A
		III	0.79C	0.91A	1.89AB	2.15AB	22.63A	24.80A	66.59A
	Top		1.68a	0.56a	1.89a	2.42a	21.05a	23.46a	66.15a
	Middle		2.00a	0.46a	1.69a	2.07a	21.24a	23.31a	66.12a
	Bottom		1.58a	0.60a	1.73a	1.99a	22.45a	24.40a	67.51a
6M Water stored		I	0.74A	0.22A	4.52A	2.10B	23.83A	25.93A	62.86B
		II	0.76A	0.23A	4.86A	2.96A	21.89B	24.85A	66.02A
		III	0.75A	0.25A	5.12A	3.06A	24.00A	25.98A	66.29A
	Top		0.66a	0.33a	4.53a	2.71a	23.43a	26.11a	64.68a
	Middle		0.81a	0.20a	5.18a	2.60a	22.92a	25.52a	64.76a
	Bottom		0.79a	0.16a	4.78a	2.84a	23.37a	25.13a	65.74a
6M Air dried		I	2.71A	0.27B	1.38A	2.26A	28.59A	30.85A	65.91B
		II	2.11A	0.22B	0.90A	1.81A	30.25A	32.06A	72.83A
		III	2.01A	0.65A	0.98A	2.45A	29.45A	31.31A	73.95A
	Top		2.19a	0.39a	1.23a	2.19a	30.58a	32.77a	66.91b
	Middle		2.13a	0.41a	1.10a	2.26a	28.36a	30.63a	71.23ab
	Bottom		2.49a	0.35a	0.94a	2.06a	29.35a	30.72a	74.54a
12M Water stored		I	0.91A	0.30A	3.40A	2.73A	22.57A	25.30A	63.81A
		II	0.60A	0.25B	2.87A	2.24A	22.43A	24.74A	64.71A
		III	0.61A	0.42A	3.81A	2.54A	22.99A	25.53A	67.27A
	Top		0.71a	0.37a	3.35a	2.32a	21.46a	25.75a	65.31a
	Middle		0.81a	0.26a	4.05a	2.63a	23.35a	25.98a	65.07a
	Bottom		0.61a	0.35a	2.68a	2.56a	23.19a	23.77a	65.40a

Table 1 (continued).

Storage condition	Position	Age class	Ash	SiO_2	Ethanol–benzene extracts	Lignin			Holocellulose
						Acid-soluble	Acid-insoluble	Lignin	
12M Air dried		I	2.21A	0.38B	2.56A	1.58B	22.47B	24.05B	64.37A
		II	1.60B	0.34B	2.00A	2.51A	24.13AB	26.64AB	62.47B
		III	1.18B	0.57A	1.79B	2.11AB	27.38A	28.68A	64.92A
	Top		1.50a	0.45a	2.37a	1.99a	23.98a	25.97a	64.42a
	Middle		1.64a	0.37a	2.22a	1.85a	23.26a	25.12a	63.88a
	Bottom		1.85a	0.48a	1.76a	2.35a	26.73a	28.28a	63.47a

Capital letters (A, B, C) in the same column denote the statistical difference of the chemical compositions among different culm ages at $P < 0.05$ according to LSD. Lower case letters (a, b, c) in the same column denote the statistical difference of the chemical compositions in different portions at $P < 0.05$ according to LSD.

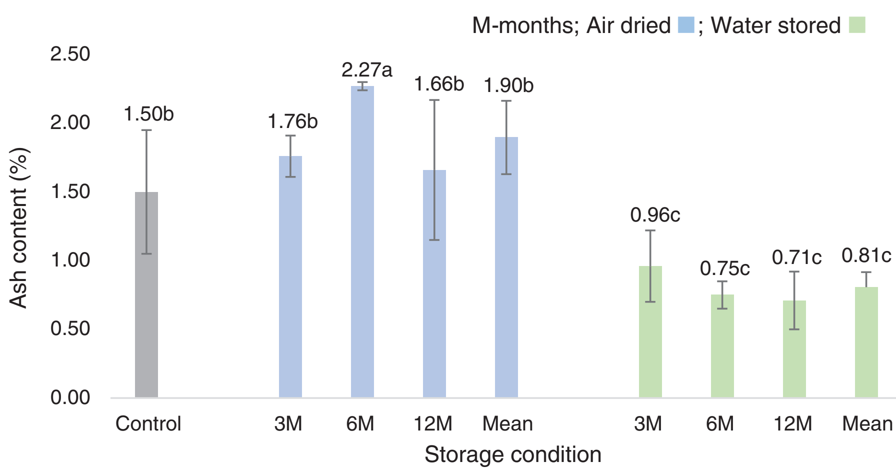

Figure 1: Ash variations of *P. edulis* culms under different storage conditions. Bars are mean values of the different age class of *P. edulis* culms in the chemical properties parameters from three replicates. Lower case letters (a, b, c after the values) denote the statistical difference of chemical properties under different conditions at $P < 0.05$ according to LSD tests (the same hereinafter)

Under the air-dry condition, the SiO_2 content of *P. edulis* culms increased to 0.54% in the 3rd month, which was significantly higher than that of the control, but deceased slightly in the 6th and 12th month. Whereas, under the water storage condition, the SiO_2 content did not show obvious change compared with that of the control, but its mean value was significantly lower than that under the air-dry condition. The lowest value was found in the 6-month culm (0.23%), which might be caused by soluble silicon dissolution in water (Fig. 2).

Under the air-dry condition, the ethanol-benzene extract of the culms showed an obviously decreasing trend, and the lowest value occurred in 6-month culm (1.09%). While under the water storage condition, the ethanol-benzene extract declined in the 3rd month, but did not show significantly decreasing trend in the 6th and 12th month (Fig. 3). The ethanol-benzene extract of the culms water stored for 6 and 12-month demonstrated insignificant difference as compared to the control. Water storage condition did not significantly affected the contents of ethanol-benzene extract in the culms (Fig. 3). Li et al. [14] reported extractives deposition increased with bamboo age and imparted greater decay resistance. Higher extractives contents might be advantageous for decay resistance and would provide good strength in fiber processing [15]. The air-dry ones showed relatively lower value on extracts than that of the control, which might have decomposed during storage. However, the ethanol-benzene extracts of the culms were preserved better under water storage conditions, which could help overcome its biologically perishable properties and be better for industrial application.

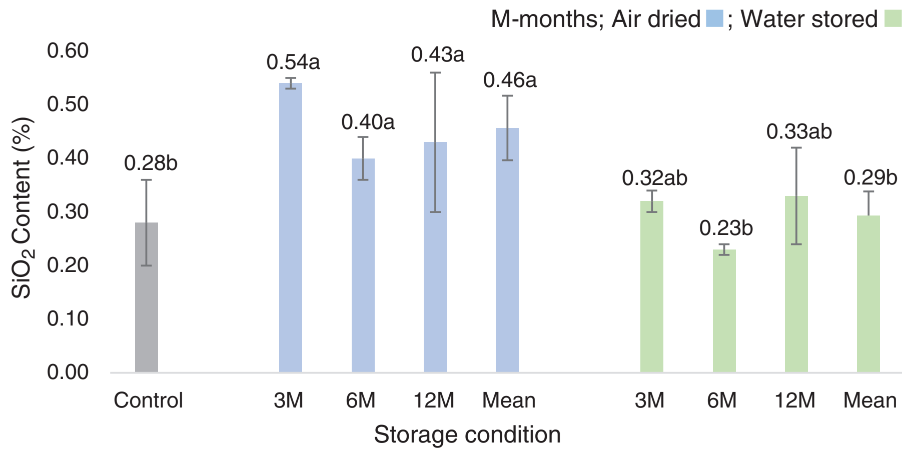

Figure 2: SiO_2 variations of *P. edulis* culms under different storage conditions

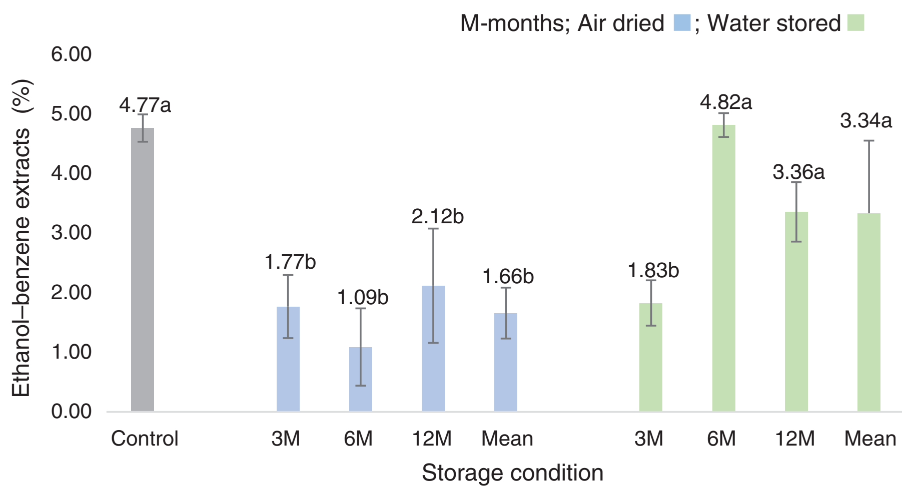

Figure 3: Ethanol-benzene extracts variations of *P. edulis* culms under different storage conditions

Under the air-dry condition, the lignin content of *P. edulis* culms decreased to 23.74% at the 3^{rd} month, but increased in the 6^{th} month and then decreased again in the 12^{th} month. The 3 and 12-month-air-dry culms had significantly lower lignin content than that of the control. Under the water storage condition, the lignin content considerably declined with the increment time (Fig. 4), which would do good to the lignin removal during pulp manufacturing, but may not be conducive to architectural applications due to its weak mechanical strength, since lignin functions as an adhesive to bind cellulose together in the fiber, making the fiber strength greater and harder to break [16], contributing to improving the physical and mechanical strength of bamboo. However, lignin is an undesirable polymer, and its removal in pulping requires high amounts of energy and chemicals [15].

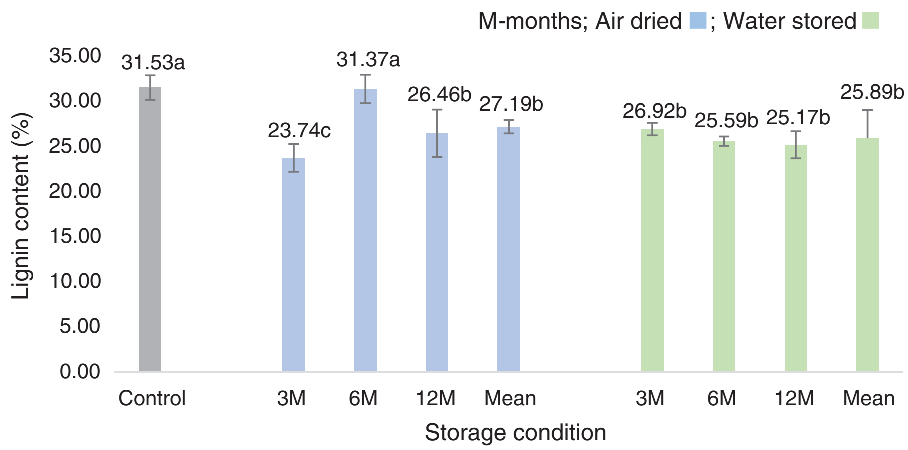

Figure 4: Lignin variations of *P. edulis* culms under different storage conditions

The holocellulose content was stable and showed no obvious difference under both the air-dry and water storage condition as compared to that of the control. In addition, no specific trend was found with the increment of storage time (Fig. 5), indicating different storage conditions had no pronounced effect on holocellulose content.

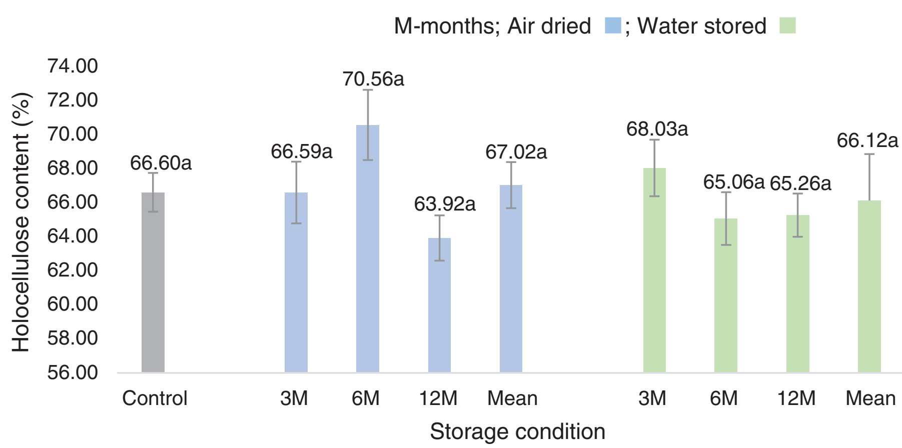

Figure 5: Holocellulose variations of *P. edulis* culms under different storage conditions

3.2 Variation of Starch and Soluble Sugar Content under Different Storage Conditions

Soluble sugar and starch are the principal forms of carbohydrate storage in vegetative tissues of plants [15]. Soluble sugar is the substrate for starch synthesis. Starch accumulation in tissues occurs when carbohydrate supply is excess of demands [17]. The starch and soluble sugar content of the *P. edulis* culms control increased with culm age (Tabs. 2 and 3). Most carbohydrates of 1-year *P. edulis* culms came from their mother bamboo, while 2-year culm had flourish branches and leaves, could producing photoassimilates by photosynthesis. Therefore, the soluble sugar content increased with culm age reached the peak in 2-year culm. However, the soluble sugar content in 3-year culm decreased, while the starch content reached the highest average value indicating that the carbohydrate supply in 3-year culm was excess of demands. It could also be noted that the starch and soluble sugar was higher in the top portions (Tabs. 2 and 3). That's because the top culm portion had flourish branches and leaves with better photosynthesis ability and more carbohydrates were produced.

Table 2: Starch content of *Phyllostachys edulis* culms under different storage conditions (%)

Age class	Position	Control	3M		6M		12M	
			AD	WS	AD	WS	AD	WS
I	Top	1.13a	1.96a	2.24a	1.54a	1.97a	1.26a	2.51a
	Middle	1.73b	2.21b	2.31a	1.53a	2.05a	2.79b	2.49a
	Bottom	2.63c	2.52b	2.76a	2.88b	2.57b	2.84b	2.16a
	Mean	1.83A	2.23A	2.44B	1.98A	2.19B	2.28A	2.38A
II	Top	2.23b	1.96a	1.71a	2.43b	1.46a	2.32b	2.62b
	Middle	1.58a	2.21ab	1.76a	1.54a	2.07b	2.34b	2.30b
	Bottom	2.16a	2.52b	1.91a	1.53a	1.61a	1.54a	1.85a
	Mean	1.94B	2.41A	1.79A	1.84A	1.77A	2.07A	2.26A
III	Top	2.68b	2.23b	1.59a	2.41a	2.05a	2.96a	1.73a
	Middle	2.14a	1.60a	1.66a	2.10a	1.97a	2.73a	2.65b
	Bottom	2.29a	2.23b	1.96a	2.77a	1.78a	2.66a	2.85b
	Mean	2.33B	1.95A	1.74A	2.43B	1.93A	2.78B	2.41A
Means	Top	2.13a	2.26a	1.83a	2.37a	1.83a	2.58a	2.48a
	Middle	2.05a	2.15a	1.93a	2.01a	2.06a	2.28a	2.37a
	Bottom	2.01a	2.07a	2.22a	1.86a	2.05a	2.36a	2.20a

Capitalized letters (A, B, C) in the same column denote the statistical difference among different culm ages at $P < 0.05$ according to LSD. Low-case letters (a, b, c) in the same column denote the statistical difference of different portions in each age group at $P < 0.05$ according to LSD (the same hereinafter).

Table 3: Soluble sugar content of *P. edulis* culms under different storage conditions (%)

Age class	Position	Control	3M		6M		12M	
			AD	WS	AD	WS	AD	WS
I	Top	3.21a	1.45a	2.03a	1.90a	1.53a	2.73a	1.77a
	Middle	2.19b	1.49a	1.95a	1.87a	1.21b	3.21a	1.72a
	Bottom	2.85b	1.46a	1.70a	1.81a	1.18b	2.09a	1.80a
	Mean	2.75AB	1.47B	1.89A	1.86A	1.31B	2.68AB	1.76A
II	Top	4.09a	3.18a	1.76a	1.66a	1.41a	2.05a	1.47a
	Middle	2.78b	3.12a	1.88a	1.43a	1.25a	2.27a	1.64a
	Bottom	2.95b	2.65a	1.74a	1.67a	1.32a	1.99a	1.43a
	Mean	3.27A	2.99A	1.79A	1.59B	1.33B	2.11B	1.52AB
III	Top	2.75a	2.98ab	2.21a	1.99a	1.64a	4.00a	1.69a
	Middle	2.60a	3.85a	1.76b	2.23a	1.43a	3.15b	1.34a
	Bottom	2.52a	2.24b	1.88ab	1.97a	1.44a	3.16b	1.38a
	Mean	2.63B	3.05A	1.95A	2.06A	1.51A	3.44A	1.47B
Means	Top	3.35a	2.54ab	2.00a	1.85a	1.53a	2.93a	1.64a
	Middle	2.52b	2.52a	1.86a	1.84a	1.30b	2.88a	1.57a
	Bottom	2.77b	2.12b	1.77a	1.82a	1.31b	2.41a	1.54a

The biologically perishable properties of bamboos are assumed to be mainly caused by its high sugar and starch contents, which are excellent foods for fungi or insects [8]. Previous investigations into the damage by the insect *Dinoderus minutus*, which was a serious pest of bamboo, showed that the damage by the pest increased with the starch contents in the bamboo culms [18]. In the present research, under the air-dry condition, the average starch content of *P. edulis* culms slightly increased but did not show considerable difference compare with that of the control. Whereas, under the water storage condition, the starch content deceased minimally in the 3rd and 6th month, and then increased to 2.35% in the 12th month. It was noticed that the mean starch content of the *P. edulis* culms under the water storage condition was lower than those under the air-dry condition (Fig. 6).

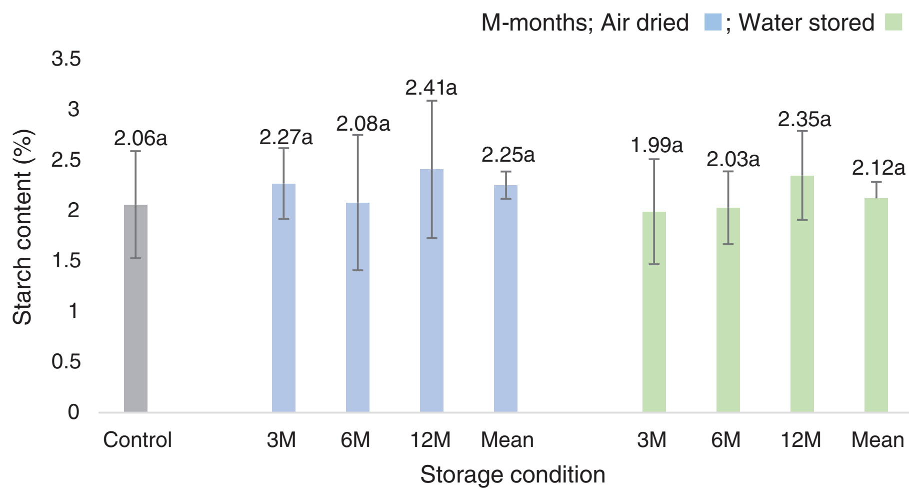

Figure 6: Starch variations of *P. edulis* culms under different storage conditions

Under the air-dry condition, the soluble sugar content of *P. edulis* culms decreased as compared with that of the control. The culms in the 3rd month (2.48%) and 6th month (1.84%) had significantly lower soluble sugar content than that of the control (2.88%), indicating some soluble sugar might be decomposed in water. Under water storage condition, the soluble sugar also decreased and had considerable lower mean value than that of the control as well as that under the air-dry condition (Fig. 7).

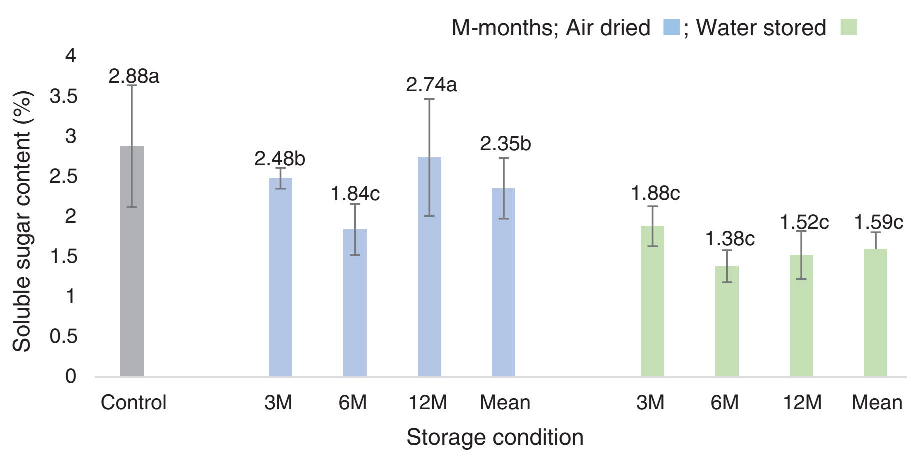

Figure 7: Soluble sugar variations of *P. edulis* culms under different storage conditions

In our study, both the starch and the soluble sugar content of the *P. edulis* culms decreased under water storage condition. Water storage created an anaerobic environment for bamboo culms in which only anaerobic respiration was possible during the storage period. This would reduce the content of soluble sugar and starch, thereby beneficial for decreasing the damage from insects and microorganisms. This was the probable reason for the indigenous practice of local people to store bamboo culms in ponds.

3.3 Variation of Mechanical Properties under Different Storage Conditions

The physical and mechanical properties of bamboo depend on many factors such as species, season, soil, height, age, presence of node section, environmental conditions [19]. The higher the value was, the stronger the strength and the better the material properties are. The main mechanical properties of the *P. edulis* culms control were compressive strength 72.50 MPa, bending strength 137.50 MPa, and tensile strength 225.43 MPa (Tab. 4). Mechanical properties of the controlled *P. edulis* culms varied with culm age, confirming the previous findings [13,19]. The compressive strength increased to 74.26 MPa at 2-year culm, but degraded slightly to 73.62 MPa at 3-year culms. The bending strength also exhibited an increasing trend with culm age, and the 2 and 3-year culms of which was notably higher than that of 1-year culm. The tensile strength increased and attained the highest value of 248.88 MPa at 3-year (Tab. 4).

Table 4: Mechanical properties of *P. edulis* culms under different storage conditions (MPa)

Age class	Position	Control	3M		6M		12M	
			AD	WS	AD	WS	AD	WS
I	Compressive strength	69.62a	52.94b	50.08b	48.06b	56.85b	65.89a	61.69b
	Bending strength	124.08b	109.17b	123.55b	71.23c	135.25b	84.96c	191.06a
	Tensile strength	210.79a	204.98a	195.42a	213.94a	183.58a	219.48a	202.71a
II	Compressive strength	74.26a	43.99b	58.01ab	53.67ab	53.00ab	67.53a	57.85ab
	Bending strength	148.29a	106.37b	115.23b	119.49b	142.28a	109.51b	124.08ab
	Tensile strength	216.63b	219.32b	207.13b	243.58a	220.69b	256.21a	234.80a
III	Compressive strength	73.62a	58.74ab	48.83b	59.61ab	50.76b	69.23a	60.57ab
	Bending strength	140.14a	79.82c	105.42b	107.82b	133.17a	119.96b	114.74b
	Tensile strength	248.88a	256.90a	204.23b	206.66b	187.74c	240.13a	208.19b
Means	Compressive strength	72.50	51.89	52.31	53.78	53.54	67.55	60.04
	Bending strength	137.50	98.45	114.73	99.51	136.90	104.81	143.29
	Tensile strength	225.43	227.07	202.26	221.39	197.34	238.61	215.23

Low-case letters (a, b, c) in the same row denote the statistical difference of the mechanical properties under different conditions at $P < 0.05$ according to LSD.

The compressive strength of the *P. edulis* culms under different storage conditions decreased obviously as compared to that of the control. Under the air-dry condition, the compressive strength decreased to 51.89 MPa in the 3rd month, but increased to 67.55 MPa in the 12th month, which showed no significant difference as compared to that of the control. The compressive strength of the *P. edulis* culms under the water storage condition showed the same decreasing trend. The difference in compressive strength between the culms under the air-dry condition and the water storage condition was not significant (Fig. 8).

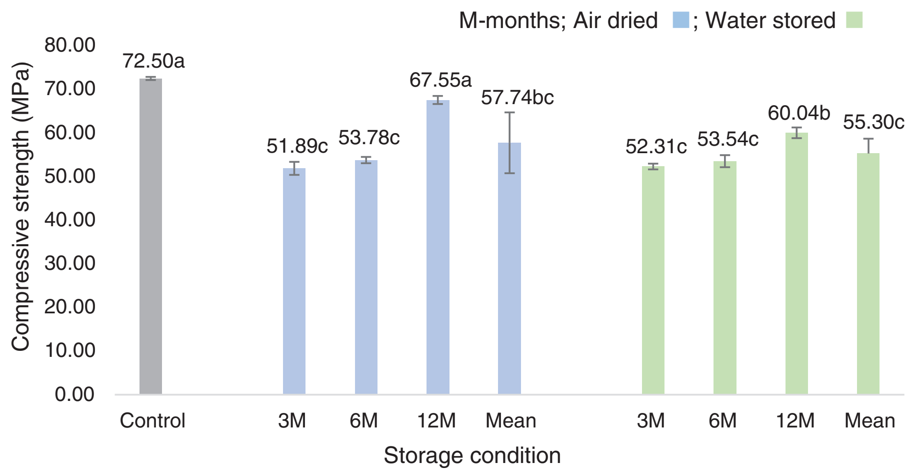

Figure 8: Compressive strength variations of *P. edulis* culms under different storage conditions

In terms of furniture manufacturing, bending strength appears to be an important material property of wood [20]. The bending strength of *P. edulis* culms demonstrated an increasing trend along with the increment time under different storage conditions. Under the air-dry condition, the bending strength decreased, significantly lower than that of the control, whereas those under the water storage condition for 6 and 12 months appeared insignificant difference as compared to that of the control (Fig. 9), indicating that the water storage condition could better maintain culm bending strength.

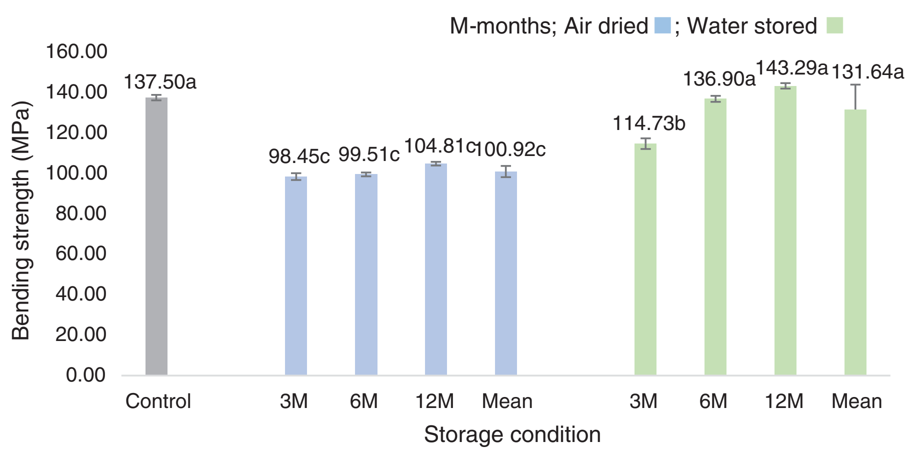

Figure 9: Bending strength variations of *P. edulis* culms under different storage conditions

Under the air-dry condition, the mean tensile strength of the *P. edulis* culms did not show obvious change as compared to that of the control (Fig. 10). Whereas, under the water storage condition, with the increment of the storage time, the tensile strength degraded to 197.34 MPa in the 6^{th} month, but increased to 215.23 MPa in the 12^{th} month, showed no significant difference compared to that of the control, implying the tensile strength was less affected under different storage conditions.

There are some explanations for strength reduction based on earlier research, such as decreasing equilibrium moisture content of wood and volumetric expansion, degradation of wood components (cellulose and especially the hemicelluloses), and evaporation of extractives [20]. Strength changes were also caused by increase of crystallinity and increased size of crystals [20]. Our study showed different storage condition caused changes in chemical composition of the *P. edulis* culm, specifically the degradation of the ash, SiO_2, extractives and lignin. Thus, the mechanical properties of *P. edulis* culm degraded, especially the compressive strength. Relatively speaking, water storage condition could better maintain their mechanical performance than the air-dry condition.

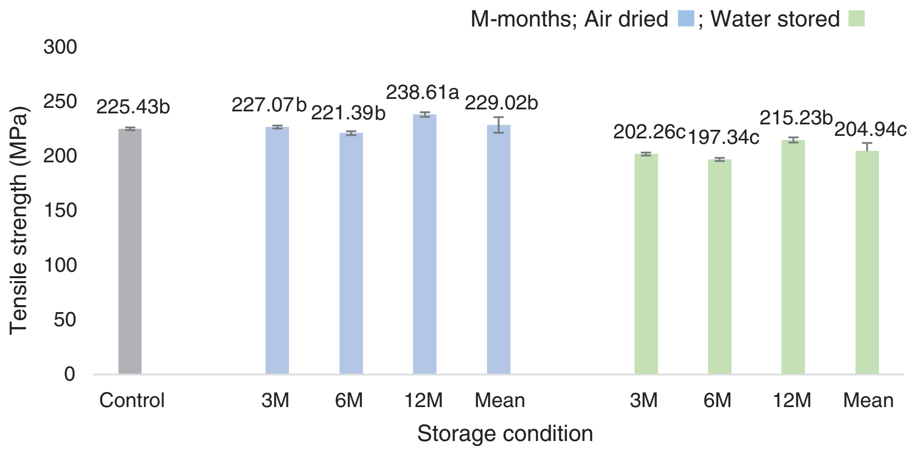

Figure 10: Tensile strength variations of *P. edulis* culms under different storage conditions

4 Conclusions

The chemical and mechanical properties of *P. edulis* bamboo culms varied under different storage conditions. The chemical properties of *P. edulis* bamboo culms varied with culm age, but insignificantly with culm height. Water storage condition decreased the ash, SiO_2 and lignin content, but increased the ethanol-benzene extracts. It also created an anaerobic environment for bamboo culms in which only anaerobic respiration was possible contributing to reducing the content of soluble sugar and starch, thereby beneficial for decreasing the damage from insects and microorganisms. The mechanical properties of *P. edulis* culms showed an increasing trend with culm age. Water storage conditions could maintain the mechanical properties of the culm better. Accordingly, *P. edulis* culms stored under water were better than under the air-dry condition. The indigenous practice of local people to store bamboo culms in ponds has good science behind it and water storage practices of bamboo culms was recommended.

Author Contributions: Hui Zhan designed the experiment, ran the data analysis and wrote the paper; Zhaohui Niu and Lixia Yu performed the experiments; Maobiao Li revised the manuscript; Changming Wang and Shuguang Wang designed the experiment, supervised the research work and revised the manuscript.

Funding Statement: This work was jointly supported by Yunnan Fundamental Research Project of 2020 (202001AT070108); Yunnan Provincial Joint Special Project for Basic Research in Agriculture (No. 2017FG001-092); Scientific Research Start-up Fund Project of Southwest Forestry University (No. 111817) and Yunnan Provincial Department of Education Fund for Scientific Research (No. 2020J0413).

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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