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Chemical composition and solubility properties of *Bambusa bambos* at different ages and height positions

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ABSTRACT

Sustainable materials are becoming increasingly important due to environmental concerns and the energy crisis. Non-wood resources such as bamboo are being explored as alternatives to wood-based materials to reduce deforestation. However, the chemical properties of these resources determine their usability. This study analyzed the chemical composition and solubility of *Bambusa bambos* (L.) Voss, a type of bamboo. The effects of age and height position (top, middle, and bottom) on the chemical composition and solubility were also considered. The study followed the standards of TAPPI (Technical Association of the Pulp and Paper Industry) to analyze holocellulose, lignin, and extractive content, and water (hot and cold) and caustic soda (1% NaOH) solubility. The results showed that the chemical composition, i.e., holocellulose, lignin, and extractive, increased while solubility, i.e., cold water, hot water, and NaOH, decreased with the ageing of *B. bambos*. The average holocellulose, lignin, and extractive contents of three-year-old *B. bambos* were 70.49%, 27.55%, and 4.54%, respectively. These values were within the range of previous studies, indicating that *B. bambos* has potential applications in various purposes.

1. Introduction

In recent years, there has been a growing interest in sustainable and renewable materials that can be used to create low-carbon products for various applications. As such, researchers worldwide are interested in the development of renewable, sustainable, and biocompatible products. Biomass materials are particularly popular due to their wide availability and compatibility with green development (AliAkbari et al. 2021). There has been significant interest from researchers in developing products for society using both wood (Das et al. 2023b; Das et al. 2023a; Rahman et al. 2014; Rahman et al. 2013) and non-wood (Das et al. 2014; Das et al. 2020; Das et al. 2015a; Das et al. 2015b) materials. With the global demand for lignocellulosic products on the rise, the overall demand for wood has also increased (Das et al. 2023a; Elias et al. 2017; Shanu et al. 2015). However, the available wood supply is expected to decrease due to the growing demand for wood products (van der Lugt et al. 2008). As a result, there has been a growing emphasis on finding alternative raw materials to replace wood (Das et al. 2016; Hossain et al. 2022a; Hossain et al. 2022c; Islam et al. 2013). Non-wood alternatives have been researched extensively due to their numerous benefits, wide availability, and comparable material characteristics (Das et al. 2015a; Das et al. 2015b; H'ng et al. 2017; Royer et al. 2012; van der Lugt et al. 2008). For example, bamboo is an excellent substitute for pulp production (Rasheed et al. 2020; Sadiku et al. 2017), nanofiber extraction (Visakh et al. 2012), composite materials (Amada et al. 1997; Chiu and Young, 2020; Das et al. 2012; Jain et al. 1992; Muhammad et al. 2019), and biofuel production (Sun et al. 2014; Yang et al. 2019). As such, it plays a major role in mitigating the pressure on slow-growing forest resources.

Bamboo is a fascinating and versatile plant that belongs to the grass family (Poaceae). It has a long lifespan and is mostly evergreen, making it a popular choice among mankind (Singh et al. 2013). Most bamboos grow as dwarf or medium-sized plants, while some can climb. It is a fast-growing plant that can grow up to 1.2 m per day and can be

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harvested within 3–5 years, yielding a high productivity of 20–40 tons per hectare per year, which is 7–30% higher than woody plants. Additionally, bamboo roots can reduce soil erosion by up to 75% (Liese and Weiner, 1996). Bamboo is a renewable resource suitable for biomass production, with great potential for socioeconomic applications (Osei et al. 2019). Furthermore, bamboo is directly related to several United Nations (UN) sustainable development goals, including poverty reduction, housing, urban development, renewable energy use, combating climate change, and land degradation (Zhao et al. 2022).

There are around 157 species of *Bambusa* worldwide, with *B. bambos* (L.) Voss being the most commonly used. It is often known as ’Giant Thorny Bamboo’ or ’Indian Thorny Bamboo’ and is native to Southeast Asia (Sharma et al. 2014). This species prefers a humid tropical climate, low to moderate elevation (less than 1000 m), and rainfall of 2000–2500 mm. *B. bambos* is known to spread and form monoculture stands in disturbed sites, along river banks and roadsides, and valleys as well as in other moist sites (Wijewickrama et al. 2020). It is used for building and scaffolding material (Pavithra et al. 2021). The spiny branches are used for fencing (Kumar et al. 2022). It has been widely used in Indian folk medicine, where the entire plant is used as an astringent, laxative, for inflammatory conditions, and as a diuretic (Aakruti et al., 2013).

Understanding the chemistry of bamboo is essential in determining many of its potential uses. For instance, a high content of lignin in bamboo fibers increases its mechanical properties, thereby strengthening the bamboo (Jansiri et al. 2021). The properties of a plant are affected by its age and height position (Majumdar et al. 2015). The amount of each chemical component found in bamboo also varies based on the species, habitat, age, location, and culm height (Liese and Weiner, 1996). As the bamboo matures, the variation in chemical composition is observed (Li et al. 2007). To use bamboo effectively, it’s important to understand how its chemical composition, i.e., holocellulose, lignin, and extractive and solubility properties, i.e., water and NaOH, change with age and height. Nevertheless, a comprehensive analysis of *B. bambos*’ varying chemical characteristics and solubility based on age and height position is yet to be documented.

This study assessed the chemical composition and solubility properties of *B. bambos* at varying ages and heights, with the aim of gaining a better understanding of how these factors impact its chemical properties and solubility.

2. Material and methods

2.1. Raw materials

B. bambos that was healthy, straight, and free of defects, aged 1 to 3 years, was gathered from Keucia silviculture research station, which is part of the Bangladesh Forest Research Institute (BFRI), located in Satkania, Chattogram (92°24’ E and 93°15’ E longitude and 24°22’ N and 25°8’ N latitude), Bangladesh. The region experiences warm and humid summers and dry and cool winters. The average maximum and minimum temperature is 30.2 °C and 12.6 °C, respectively, with a relative humidity of 79% and an annual rainfall of 2919.1 mm. The topography of the area ranges from flat to gentle slopes.

The Carolina Biological Supply Company, located in New York City, USA, provided reagent grade ($\geq$95% purity) sodium hydroxide (NaOH), acetic acid (CH_3COOH), sodium chlorite ($NaClO_2$), and sulfuric acid (H_2SO_4). Analytical grade ($\geq$95% purity) benzene and ethanol were procured from Merck KGA, located in Darmstadt, Germany.

2.2. Preparation of raw materials

To prepare the raw materials for our study, we followed the procedures described by Hossain et al. (2022a, 2022b, 2022c). We randomly selected and cut mature culms of bamboo, which had an average height of 40 feet. The culms were cut 15 cm above ground level and then divided equally into top, middle, and bottom portions based on their length. These portions were further divided into small strips. The bamboo strips were ground into small chips using a hammer mill and then dried in the sun. We used a Wiley mill to grind the dried bamboo chips into powder, which was then screened through a shaker to separate particles between 40 and 60 mesh sizes for further analysis. All ages and parts of bamboo underwent the same process. We stored the particles in airtight containers marked with appropriate codes for the analysis.

2.3. Analysis of chemical properties

A chemical analysis was conducted following previously reported procedures (Hossain et al. 2022b, c). The evaluation of holocellulose was carried out according to the T 249–75 standard, while the Klason lignin was examined based on the T-222 cm-02 standard. Extractive content was determined using the T-204 cm-97 standard, whereas solubility in cold and hot water was evaluated using the T-207 cm-99 standard. The solubility in an alkaline solution (1% caustic soda (NaOH)) was measured using the T-212 om-02 standard. The bamboo samples were analyzed at least three times, and the mean values were recorded.

2.4. Data analysis

To examine the impact of age and height on chemical compositions and solubility, a one-way analysis of variance (ANOVA) was performed with the Duncan similarity test. IBM SPSS Statistic-22 was used for this analysis, while spreadsheet-2019 was utilized to generate the graphs.

3. Results and discussion

3.1. Holocellulose

Fig. 1 presents the impact of age and height position on the holocellulose content of *B. bambos*. The lowest holocellulose content (61.4%) was found in the bottom part of one-year-old bamboo, while the highest (71.1%) was found in the top portion of three-year-old bamboo. The average holocellulose content varied between one (61.6%), two (64.7%), and three (70.5%) year-old bamboos. Overall, there was an increasing trend in holocellulose content with an increase in the age and height position of the bamboo. Three-year-old *B. bambos* showed a higher amount of holocellulose content on average (14.4% and 9.03% compared to one and two-year-olds, respectively). The top part of three-year-old *B. bambos* had a higher holocellulose content of 0.48% and 2.27% compared to the middle and bottom parts, respectively. The increase in holocellulose content slowed down with increasing age. The difference in height positions decreased when moving towards the top. ANOVA analysis revealed a significant effect ($p < 0.05$) of age on holocellulose content, while there is no significant ($p > 0.05$) difference in

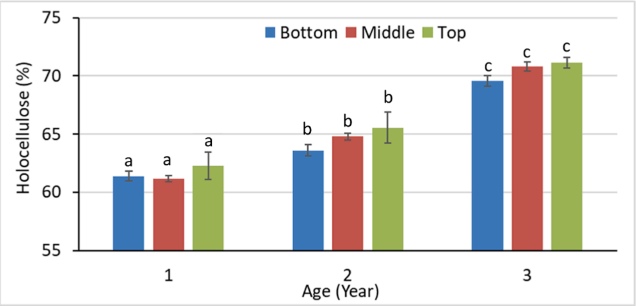

Fig. 1. Holocellulose content of *B. bambos* at different ages and height positions; Similar letters refer to insignificant ($p > 0.05$) difference.

height positions and holocellulose content (Fig. 1). Similar trends have been observed by Li et al. (2007) in *Phyllostachys edulis* (Carrière) J. Houz., but the reverse has been seen in *Melocanna baccifera* (Roxb.) Kurz by (Hossain et al. 2022a). The holocellulose content increases when a greater vascular bundle is present at the top (Wang et al. 2011). Holocellulose increases more slowly as it ages due to the higher amount of lignin, ash, silica, and other extractive elements (Hisham et al. 2006). Generally, bamboo becomes mature in three years (Kleinhenz and Midmore, 2001). Holocellulose has a significant impact on the quality of composite boards (Sarı et al. 2014) and the yield of paper pulp (Macleod, 2007). As the holocellulose content of a three-year-old *B. bambos* culm falls within the range of wood species (62 to 79% in wood (Bao et al. 2001)), it could be a possible source of raw materials for the production of pulp and paper, bioenergy, and biobased composites.

3.2. *Klason lignin*

Fig. 2 presents the impact of age and height position on the lignin content of *B. bambos*. The lowest lignin content, at 22.3%, was found in the top portion of one-year-old *B. bambos*, whereas the highest lignin content, at 28.7%, was found in the bottom portion of three-year-old *B. bambos*. The average lignin content for *B. bambos* of different ages showed the lowest values for one-year-old, at 22.5%, followed by two-year-old, at 25.3%, and three-year-old, at 27.6%. As *B. bambos* ages, the average lignin content increased, with three-year-old *B. bambos* having 22.5% and 8.97% higher lignin content than one-year-old and two-year-old *B. bambos*, respectively. The top portion of the three-year-old *B. bambos* had a lower lignin content of 6.58% and 0.89% compared to the bottom and middle portions, respectively. Lignification decreased with ageing, and the lignin content decreased as the height increased (Fig. 2). ANOVA analysis revealed that age had a significant effect ($p < 0.05$) on lignin content, while there was no significant ($p > 0.05$) difference in height position and lignin content. These findings are similar to observations made on *P. edulis* by Li et al. (2007) regarding the effect of age and height position on lignin content. However, the effect of height position on lignin content contrasts with the findings of *M. baccifera* by Hossain et al. (2022a), while it is similar to the effect of age. The biosynthesis of lignin is dependent on several factors including environment and species (Biswas et al. 2022), which may explain the differences in the observations. Lignin content ranges from 24% to 37% for softwoods and 17% to 30% for hardwoods (Dence, 1992). Researchers have observed the lignin content of *P. pubescens* in the range of 19.7% to 28.5% (Huang et al. 2008). The amount of lignin in *B. bambos* is comparable to that of wood and other bamboo species. Greater lignin content hinders delignification, which is problematic for producing pulp, paper, and biobased composites. However, lignin may also be used in biorefineries to make lignin products. *B. bambos* has the largest holocellulose content, especially at maturity (three years). For the biorefinery process, 3-year-old bamboo is a viable source of raw materials since lignin content does not change significantly after three years. Delignification should take into account the variation in lignin content. More research is needed to determine the best lignification ages and cost-benefit analyses for product development.

3.3. *Extractives*

According to data presented in Fig. 3, the extractive content varied based on the age and height position of *B. bambos*. The highest extractive content, at 4.96%, was found in the bottom part of a three-year-old *B. bambos*, while the lowest extractive content, at 0.81%, was found in the top part of a one-year-old *B. bambos*. Gradually increasing values were observed across age graduations of one (1.39%), two (3.55%), and three-year-old (4.54%) *B. bambos*. The extractive content increased by 228% between one-year-old and three-year-old *B. bambos*, and by 28.1% between two-year-old and three-year-old *B. bambos*. Height position also influenced extractive content, with the top portion having 27.2% and 22.3% less extractive content than the bottom and middle portions, respectively for three-year-old *B. bambos*. These results indicate that extractive content increases with the ageing of *B. bambos*, and that the values of extractive content between height positions are more or less similar. ANOVA analysis confirmed that age had a significant effect ($p < 0.05$) on extractive content, while there was no significant ($p > 0.05$) difference in height position and extractive content. These findings are consistent with those of Hossain et al. (2022a) for *M. baccifera*, but differ from those of Li et al. (2007) for *P. edulis*. Higher extractive contents can hinder further processing and delignification. However, a higher extractive content can also protect against biodegradation and be advantageous for certain bio-based composites. Therefore, three-year-old *B. bambos* may be better suited for anti-decay and exterior usage, but further research is needed to determine the best way to use it.

3.4. *Solubility*

3.4.1. *Water solubility*

In Fig. 4, the cold (Fig. 4 A) and hot (Fig. 4B) water solubility content of *B. bambos* is shown to be affected by age and height position. Hot water solubility was greater than cold-water solubility, and both types decreased with increasing age and height. The average cold-water solubility was 7.42%, 6.97%, and 5.52% for one, two, and three-year-old *B. bambos*, respectivelyrespectively. The bottom part of one-year-old bamboo showed the highest (7.62%) cold-water solubility, while the top portion of three-year-old bamboo showed the lowest (4.58%) value. Similarly, the average hot water solubility values were observed in the age graduation of one (8.63%), two (7.41%), and three-year-old (5.26%) *B. bambos*. The bottom part of one-year-old bamboo showed the highest (9.30%) hot water solubility, while the top portion of three-year-old bamboo showed the lowest (4.68%) values. The bottom position of all age classes gave the higher value of cold and hot water soluble compared to other portions. The ANOVA analysis revealed that the effect of age on

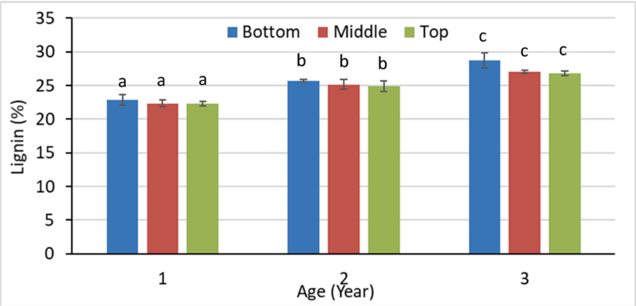

Fig. 2. Klason lignin content of *B. bambos* at different ages and height positions; Similar letters refer to insignificant ($p > 0.05$) difference.

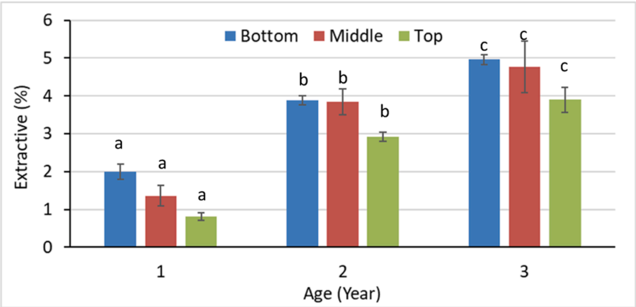

Fig. 3. Extractive content of *B. bambos* at different ages and height positions; Similar letters refer to insignificant ($p > 0.05$) difference.

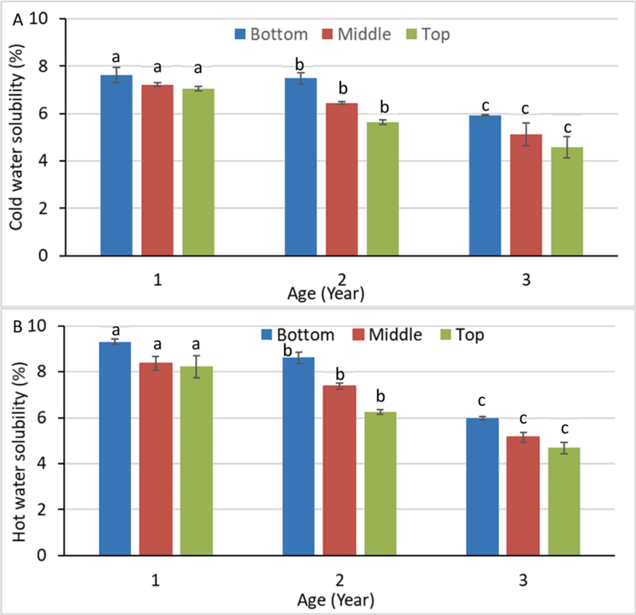

Fig. 4. (A) Cold water solubility and (B) hot water solubility of *B. bambos* at different ages and height positions; Similar letters refer to insignificant ($p > 0.05$) difference.

the cold and hot water solubility was significant ($p < 0.05$), while it was insignificant ($p > 0.05$) based on the height positions. Similar observations have been made for *M. baccifera* (Hossain et al. 2022a), but the effect of height positions was significant in their study. The presence of fewer extractives according to the height position may result in low solubility. Furthermore, ageing may help to prevent water penetration, forming more dead cells leading to less solubility. Water-soluble extractives such as sugars are removed during the water pre-extraction process. Heat-assisted water extraction can improve the extracted materials.

3.4.2. Caustic soda solubility

The solubility of *B. bambos* in caustic soda (1% NaOH) varied with age and height, as depicted in Fig. 5. As the age and height of the bamboo increased, the NaOH solubility decreased. The average values were observed in the age groups of one-year-old (26.4%), two-year-old (23.6%), and three-year-old (21.9%) *B. bambos*. The NaOH solubility of the bottom part of one-year-old bamboo was the highest (27.3%), while the top portion of three-year-old bamboo had the lowest (21.2%) value. NaOH solubility was significantly ($p < 0.05$) affected by ageing, but the height position had an insignificant ($p > 0.05$) effect in this study. A similar effect of age and height was recorded for *M. baccifera* (Hossain et al. 2022a). As the bamboo ages, the extractive and lignin contents rise (Li et al. 2007), which was observed in *B. bambos* in this investigation as well. This rise in extractive and lignin contents may hinder *B. bambos* from soluble low molecular weight carbohydrates in a 1% NaOH solution.

4. Conclusion

This study examined the chemical properties of *Bambusa bambos*, which varied based on age and height position. Age had a significant effect on chemical composition and solubility, while height position did not have a significant effect. The levels of holocellulose and lignin content of *B. bambos* were similar to those found in wood and other bamboo species. Further research on the effects of age in downstream processes such as pulping and bioethanol production may reveal more potential applications.

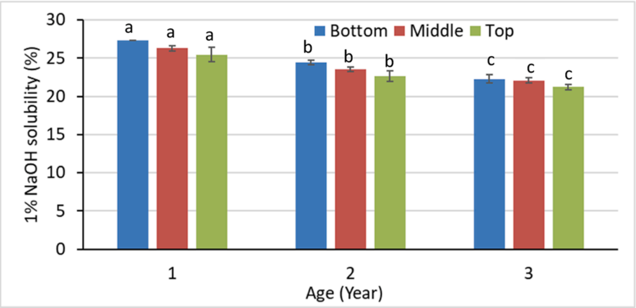

Fig. 5. Caustic soda (1% NaOH) solubility of *B. bambos* at different ages and height positions; Similar letters refer to insignificant ($p > 0.05$) difference.

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CRediT authorship contribution statement

Islam Md. Rakibul: Writing – review & editing, Investigation. **Nath Shambhu Chandra:** Writing – review & editing, Investigation. **Sudiyani Yanni:** Writing – review & editing, Validation. **Maryana Roni:** Writing – review & editing, Validation, Formal analysis. **Hossain Mohammad Jakir:** Writing – review & editing, Supervision, Funding acquisition. **Ghosh Rupak Kumar:** Writing – original draft, Formal analysis, Data curation. **Das Atanu Kumar:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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