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Synthesis and Characterization of Cellulose-Based Hydrogel from Furniture Waste as a Sustainable Plant Growth Medium

Sintesis dan Karakterisasi Hidrogel Berbasis Selulosa dari Limbah Kayu Mebel sebagai Media Tanam Berkelanjutan

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ABSTRAK

Sumber biomassa yang berasal dari limbah kayu industri furnitur belum banyak dimanfaatkan. Dalam penelitian ini, selulosa diekstraksi dari limbah kayu furnitur melalui beberapa tahap. Tahap pertama yaitu maserasi menggunakan etanol dilanjutkan hidrolisis menggunakan asam nitrat. Delignifikasi menggunakan basa, dilanjutkan dengan tahap pemutihan menggunakan hidrogen peroksida. Proses tersebut menghasilkan selulosa murni sebanyak 30% dengan kadar abu dan kadar air yang rendah (berturut-turut 0.56 dan 2,6%). Struktur selulosa dikonfirmasi melalui karakterisasi dengan FTIR. Munculnya serapan khas O–H, C–H, dan C=O menandakan selulosa telah berhasil diisolasi. Selulosa kemudian diikat silang dengan glutaraldehida untuk menghasilkan hidrogel (WWF hidrogel). Hidrogel ini mempunyai daya serap air yang tinggi dan stabil secara struktural. Uji coba aplikasi hidrogel sebagai media tanam untuk Dracaena sanderiana (bambu hoki) menunjukkan bahwa hidrogel WWF meningkatkan pertumbuhan tanaman sebesar 4,5% selama 10 hari, lebih besar dibandingkan dengan hidrogel komersial, yaitu sebesar 1,79%. Hasil ini menunjukkan bahwa hidrogel berbasis selulosa yang berasal dari limbah furnitur dapat berfungsi sebagai media tanam dengan penahan air yang efektif. Selain itu, material baru ini juga memberikan alternatif pemanfaatan limbah kayu yang berkelanjutan untuk meningkatkan nilainya.

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ABSTRACT

Biomass resources from furniture wood waste have not been widely used. In this study, furniture wood waste biomass was used as a cellulose source. Isolation of cellulose from furniture waste was carried out through a sequential process comprising maceration, hydrolysis, delignification, and bleaching. In this study, 30% purified cellulose was obtained from furniture waste, with 0.56% ash and 2.6% moisture content. FTIR spectra revealed that the structure of cellulose consisted of O-H, C-H, and C=O bands. Cellulose was then crosslinked with glutaraldehyde to form hydrogels (WWF hydrogel). This hydrogel has a high swelling and high structural stability. As a growth medium for Dracaena sanderiana (lucky bamboo), WWF hydrogel increased plant growth by 4.5% in 10 days. This is higher than that of commercial hydrogel, which is only 1.79%. These results confirmed that cellulose-based hydrogels derived from furniture waste could act as an effective water-retaining growth medium. Also, this new material offers a sustainable utilization pathway for increasing the value of biomass from furniture waste.

1. INTRODUCTION

1.1 Background

According to the data from BPS-Statistics Indonesia in 2022, there are 1.357 furniture industries widely spread in Indonesia. Many furniture manufacturers produce large amounts of wood waste during production, such as sawdust and wood shavings. All this waste is commonly only discarded without further use. This condition not only becomes an environmental problem but also wastes the abundant potential of biomass (Kurniasih et al., 2022). Furniture waste contains a polymer consisting of cellulose, lignin, and hemicellulose. Cellulose can be extracted from this biomass through a sequential process including delignification, hydrolysis, and bleaching (Peng et al., 2011; Phanthong et al., 2018). Cellulose can be used or transformed into useful biomaterials such as hydrogels. This is supported by its biodegradability, biocompatibility, and modifiability (Klemm et al., 2005; Wang et al., 2023).

A hydrogel is a three-dimensional polymer formed by crosslinking through chemical or physical interactions, so it can hold more water molecules. Hydrogel is widely used in various fields, including medicine, packaging, energy storage, and agriculture (Kabir et al., 2018; Radoor et al., 2024). Cellulose-based hydrogels are widely used in agriculture due to their ability to enhance the quality of the growth medium, retain water, and control plant growth by regulating water intake (Fekete et al., 2016; Liu et al., 2022).

As a crosslinking agent, glutaraldehyde is used to increase the water retention and mechanical strength of hydrogels. This results from the covalent bond formed between cellulose and glutaraldehyde (El-Khawaga et al., 2023). Kabir et al. (2018) reported that cellulose-based hydrogels can hold more water than soil individually. On the other hand, if compared to commercial hydrogels, cellulose-based hydrogels are more biodegradable. This is important for environmental concerns due to the accumulation of waste from hydrogels use. Therefore, this approach of transforming furniture waste into hydrogels with high cellulose content and hydrophilic activity could be a promising way to enhance plant growth and structure without worrying about waste accumulation.

Based on the explanation above, the objective of this research is to study the utilization of cellulose-based hydrogels from furniture waste biomass in Jepara, Indonesia, as a plant growth medium for Dracaena sanderiana (lucky bamboo). As far as we know, this approach is not mentioned in the literature before.

2. METHOD

2.1 Materials

The materials used in this research include furniture waste from Jepara, Indonesia; *Dracaena sanderiana* (lucky bamboo); and purified water. All reagents include ethanol 96% (*Sigma Aldrich*), HNO_3 65% (*Merck*), NaOH (Merck), Na_2SO_3 (Merck), H_2O_2 (Sigma Aldrich), glutaraldehyde (*Sigma Aldrich*), and Carboxymethyl cellulose (*Sigma Aldrich*).

2.2 Methods

Synthesis of cellulose-based hydrogels starts from the extraction of cellulose. Furniture waste was sun-dried for 6 hours, then crushed through a 20-mesh sieve. Cellulose was isolated in several steps, following Monariqsa et al. (2012) and Rusdianto et al. (2021), with modifications. Furniture waste was macerated in 96% ethanol for 72 hours. After that, the isolate was hydrolysed using 3.5% HNO_3 in 90 °C for 2 hours, followed by delignification with 2% NaOH and 2% Na_2SO_3 in 50 °C for 6 hours. The delignification results were bleached with 3% H_2O_2 at 60 °C for 30 minutes. To confirm successful isolation of cellulose from furniture waste, the isolate was analysed by Fourier Transform Infrared Spectroscopy (FTIR). Also, the ash and moisture content from isolated cellulose were measured.

The next step is to synthesis a hydrogel from isolated cellulose using glutaraldehyde as a crosslinker. First, cellulose was dissolved in 8.5% NaOH, then frozen for 24 hours and thawed. Hydrogel synthesis was performed in various glutaraldehyde:cellulose ratios (1:2, 1:4, 1:6, and 1:8 w/w). Hydrogels were then molded and used as plant growth media for *Dracaena sanderiana* (Lucky bamboo). The performance of hydrogels as growing media was evaluated by measuring the height of *Dracaena sanderiana* leaves, as well as their water absorption capacity and stability, in three replicates for each parameter.

3. RESULTS AND DISCUSSION

3.1 Isolation of Cellulose from Wood Waste Furniture

Isolation of cellulose from furniture waste was carried out in a sequential process, as illustrated in Figure 1. The furniture waste was macerated in 96% ethanol to remove the proteins, lipids, and other matrix components. After that, to remove the hemicellulose, hydrolysis with 3.5% HNO_3 was performed. This process breaks the polymer chains into simple monomers, as indicated by the solution's colour change from colourless to yellow. The byproduct at high temperatures is NO_2. The delignification process using 2% NaOH breaks the ester chain.

(a) Maceration Process

(b) After maceration process

(c) Acid Hydrolysis

(d) After acid hydrolysis

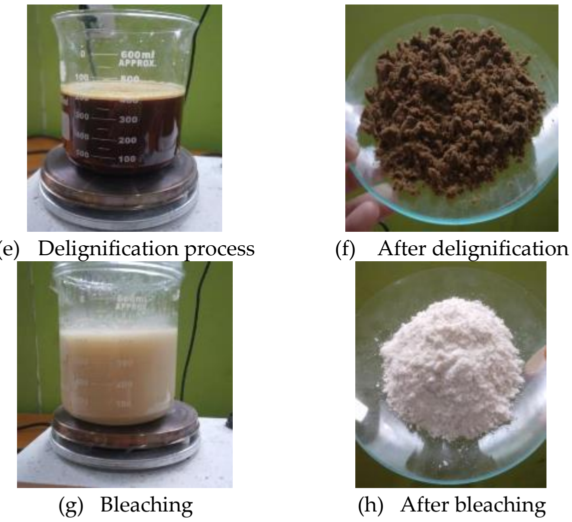

Figure 1. Sequential steps of Cellulose Isolation

Because of the strong alkali solution, there is a breaking of the ester and ether bond between lignin, cellulose, and hemicellulose. Na_2SO_3 was then used to neutralize the solution's acidity. To remove the lignin, bleaching using 3% hydrogen peroxide was performed. This process will not influence the cellulose structure (Indriati et al., 2020). In the end, pure cellulose was obtained as indicated by the sample's colour change from dark brown to white. The isolated cellulose has a fine, delicate texture and a 30% (w/w) yield (Sokanandi et al., 2014).

3.2 Characterization of Isolated Cellulose

According to Santoso et al. (2025), ash content in woody biomass is usually in 0.37–1.79%. Ash content was analyzed because it is an important indicator of inorganic residue in wood. It can change the reactivity and utility of cellulose. Following the ISO 1762:2019 method, the result of ash content in furniture waste from Jepara is 0.56%. This indicates that the materials have low concentrations of macro and micronutrients, as well as the ash content.

The moisture content of cellulose is also important because it affects dry mass and chemical reactivity. In accordance with ISO 638-1:2022, moisture content was analyzed. Cellulose powder from furniture waste has a low moisture content, it is only 2,6%. This low moisture content makes the material more stable and durable. High moisture content shortens the shelf life of materials due to degradation (Gamstedt, 2016; Jiang et al., 2022). The ash and moisture content are shown in Table 1.

Table 1. Ash and moisture contents from isolated cellulose

Parameter	Result
Ash Content	0.56%
Moisture Content	2.6%

To confirm that the isolated product is cellulose, FTIR was conducted. From Figure 2, there is a broad peak at 3348.42 cm^{-1} that corresponds to O–H stretching vibrations, while absorptions at 2916.37 cm^{-1} and 2854.65 cm^{-1} indicate $–CH_2$ stretching, confirming the polysaccharide chain in the cellulose. The ester C–O band from acetyl groups and the C=O vibration was observed at 1373.32 cm^{-1} and 1635.64 cm^{-1}, respectively. The sharp peak at 1635.64 cm^{-1}, together with the reduced O–H band intensity, suggests substitution of hydroxyl groups by acetyl groups, confirming the presence of partially acetylated cellulose (Suciyati et al., 2021).

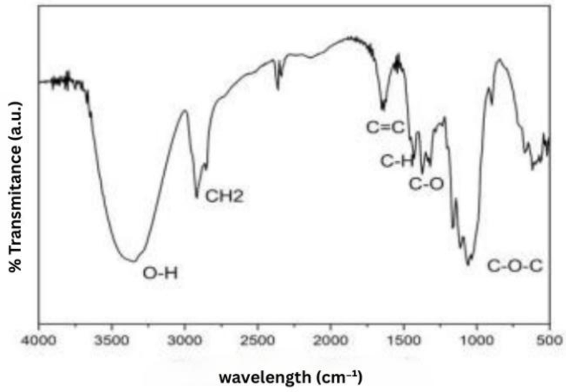

Figure 2. FTIR Spectrum of Cellulose

3.3 Synthesis of Hydrogels from Cellulose-Based Wood Waste Furniture

In the plant cell walls, cellulose is the main polymer component. Cellulose consists of a glycosidic chain linked by β-1,4-glycosidic bonds. Every D-anhydroglucopyranosic unit contains three hydroxyl groups (OH) in C2, C3, and C6 positions. This OH allows hydrogen-bond formation in the intra- and intermolecularly. Contribute to the stability and crystallinity of cellulose (Alven & Aderibigbe, 2020). Cellulose is commonly known as a raw material for the synthesis of hydrogels. This is due to its abundance, biocompatibility, biodegradability, and the reactivity of the functional groups.

In the synthesis of hydrogels, many crosslinkers can be used. The cellulose derivative determines the crosslinker used. Some crosslinkers typically contain aldehyde groups. This is because aldehydes can react with OH groups in cellulose to form a stable three-dimensional framework. The presence of crosslinkers will enhance the physicochemical and structural properties of hydrogels (Nasution et al., 2022).

Glutaraldehyde, a crosslinker, was used in this study to synthesize cellulose-based hydrogels, known as WWF Hydrogels. Glutaraldehyde is more effective as a crosslinker, forming a stable hydrogel matrix that holds more water. When held in water, WWF hydrogels swelled, but the behaviour varied with on the cellulose ratio in the hydrogels and the temperature. The excessive amount of glutaraldehyde caused the polymer chain to separate. This is a worse condition in the performance, so the glutaraldehyde ratio should be optimized to get the best condition in water holding. In the previous report, Khabibi et al. (2021) successfully synthesized chitosan/sodium carboxymethyl cellulose (CS/CMCNa)-based hydrogels using glutaraldehyde as a crosslinking agent. Their study showed that although glutaraldehyde increased the swelling capacity, larger concentrations reduced water adsorption. This is because glutaraldehyde binds to hydrophilic groups, limiting interactions with water molecules.

Figure 3. Hydrogels form furniture wood waste cellulose (WWF Hydrogels)

The physical form of the WWF hydrogels is presented in Figure 3. Figure 4 shows that the hydrogel was successfully synthesized. Crosslinking between cellulose and glutaraldehyde occurred. Large O–H stretching vibrations were found around 3200–3400 cm^{-1}, while C–H stretching near 2900 cm^{-1}, and C=O stretching of aldehyde groups around 1700 cm^{-1}. These wavelength characteristics show that there are functional groups that are linked to hydrogel structures (Rihawy et al., 2019).

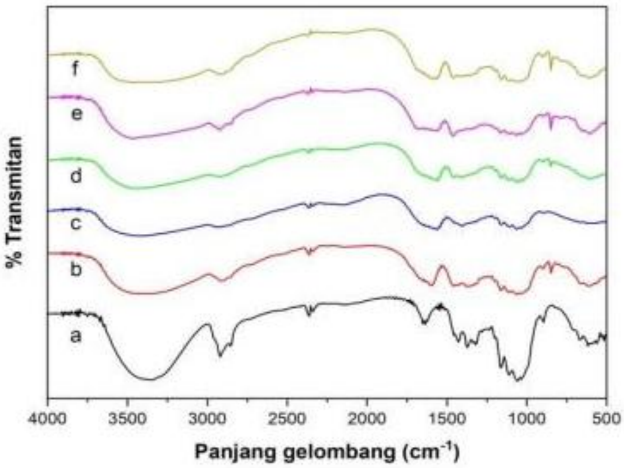

Figure 4. FTIR Spectrum of WWF Hydrogels

3.4 Swelling Ratio

The swelling ratio data are shown in Table 2. The optimum water absorption was obtained at a 1:6 cellulose-to-crosslinker ratio at 25 °C. At ratios of 1:8, 1:4, and 1:2, swelling decreased. Excessive glutaraldehyde affects the cellulose polymer chain and reduces water interaction consistently with previous research by Khabibi et al. (2021). This proves that increasing the glutaraldehyde concentration reduces hydrogel swelling. The optimum condition was found to be a 1:6 ratio at 25 °C.

Table 2. Swelling capacity of hydrogels at different cellulose-to-crosslinker ratios

Ratio of Glutaraldehyde: Cellulose	Swelling Ratio (%)
0:1	233
1:2	263
1:4	272
1:6	350
1:8	316

Without a crosslinker (0:1), the hydrogel has a lower swelling ratio. This indicates that structural stability and swelling ratio are limited. The swelling ratio increases linearly with increasing glutaraldehyde, reaching 350% in a 1:6 cellulose-to-glutaraldehyde ratio. The ideal formation of crosslinking structure supports the structural integrity and promotes water diffusion and retention. But the swelling ratio decreased to 316% when the crosslinker increased to 1:8. This is due to the excessive crosslinking, which reduces pore size and limits polymer mobility.

These results show that the best combination of structural stability and swelling capacity can be achieved at a moderate cellulose-to-glutaraldehyde ratio. Also, hydrogels' water absorption is strongly influenced by temperature, as high temperatures can disrupt the hydrogen bonds between the hydrogel and water. The three-dimensional cross-linked network can loosen, facilitating the mobility of the polymer chain within the hydrogel matrix. The swelling generally increases. Setyaningsih et al. (2020) also reported that at 25 °C, the swelling capacity increased compared with 15 °C. However, swellings reduced at 45 °C. This is due to the breakdown of the hydrogel matrix at elevated temperatures. The hydrogen bonds between polar functional groups and water molecules at lower temperatures also restricted water absorption, resulting in less ideal swelling.

3.5 WWF Hydrogel Application in Dracaena sanderiana Cultivation

WWF Hydrogels were then used to support growth of *Dracaena sanderiana.* In 10 consecutive days, as illustrated in Figure 5, WWF hydrogels were compared with commercial hydrogels. Commercial hydrogels increase plant growth 1,79% in ten consecutive days, while WWF hydrogels increase 4,5%. Increasing water uptake provides greater stability and enhances nutrient supply. This shows that WWF hydrogels have a good potential for sustainable plant growth. On the other hand, WWF hydrogels are also effective in improving the root growth in soil-less or hydrophobic systems (Kalossaka et al., 2021; Zhang et al., 2023).

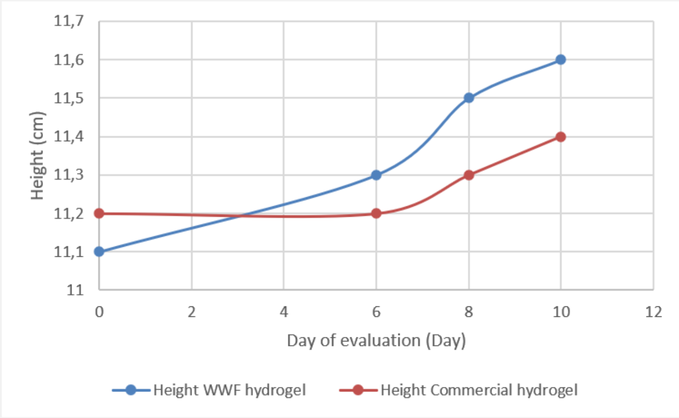

Figure 5. Curve of Height of Lucky Bamboo

4. CONCLUSION

Furniture wood waste has been synthesized into sustainable cellulose-based hydrogels. This hydrogel is of superior quality compared to the commercial one. WWF hydrogels can absorb water and enhance plant growth. Hydrogels could become an alternative and environmentally friendly material in soil-less or hydrophobic systems. In the next project, research should focus on optimizing the hydrogel formulation and evaluating the long-term biodegradability, as well as the effectiveness of hydrogels in various soil types and cultivation conditions.

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