Addition of Ethanol as a Lignin Extractor to Reduce NaOH Consumption and Fiber Degradation in the MCO₂ Stage

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ARTICLE INFORMATION

ABSTRACT

One of the stages in the pulp industry that needs a lot of NaOH is MCO₂ (Medium Consistency Oxygen). However, the production process is impeded by the highly restricted availability of NaOH. Additionally, the significant fiber degradation that frequently takes place at the MCO₂ stage may lessen the pulp’s viscosity and strength. The study’s components included pulp, ethanol, and NaOH. The goal of the research was to use less NaOH and to slow down fiber degradation by adding ethanol. The process involves adjusting the dose to obtain the optimum proportion of ethanol and NaOH, after which the temperature and reaction time are varied to produce pulp with higher quality. The results showed that at various doses, 50%:50% was the most optimum proportion of ethanol and NaOH with a kappa number 18, viscosity 1068.11 cP, and brightness 32.15% ISO. The best temperature that occurred in the optimum proportion of ethanol and NaOH was 85°C with a kappa number of 17.3, a viscosity of 1056.78 cP, and a brightness of 32.56% ISO. Meanwhile, the best reaction time for the optimum proportion of ethanol and NaOH occurred at 90 minutes with a kappa number of 15.6 viscosity of 1023.04 cP, and brightness 32.69% ISO.

INTRODUCTION

Sodium hydroxide or NaOH is one of the basic chemicals that plays an important role in the production process in various domestic industries such as the pulp and paper industry, textile industry, organic chemical industry, and others. NaOH is not only used as a supporting material but also as a main raw material. The demand for NaOH in Indonesia is quite high and continues to increase every year [1]. The import quantity of NaOH in 2018 experienced a significant increase from 44,866 tons to 64,113 tons [2]. Meanwhile, the high rate of raw material imports can hinder continuity [1] and reduce industrial productivity [3].

In the pulp industry, NaOH is used as a key component of white liquor to separate lignin from cellulose fibers in the kraft process and also plays a role in several subsequent stages, including oxygen delignification, oxidative extraction, and simple extraction [4]. According to the daily report of the fiberline department at the Palembang Pulp Industry, NaOH is the pure chemical with the highest consumption, with an average usage of 27.06 kg/ADT (Air Dry Ton Pulp). The lack of availability of NaOH can hinder many production processes in the cooking stage, MCO₂ stage, and bleaching stage.

MCO₂ is an advanced delignification process from the kraft pulping process or as an initial step before the bleaching process. However, the drawbacks in the MCO₂ process include a high level of cellulose degradation or poor selectivity [5]. Poor selectivity in MCO₂ is reflected in the data from the daily report of the fiberline department at the Palembang Pulp Industry in 2020, which shows that the average viscosity values and kappa numbers of the produced pulp did not meet the target. On the other hand, important parameters that can illustrate the success of the MCO₂
process are pulp yield, kappa number, and viscosity [6]. Indirectly, the kappa number and viscosity values that have not been achieved can reduce the effectiveness of the MCO₂ stage in saving expensive chemicals and mitigating the environmental impact from the pulp bleaching process [7].

Lignin is soluble in organic compounds, and carbohydrates are soluble in water, while cellulose is not soluble in either. The addition of ethanol, which is an organic solvent, can better minimize the degradation of cellulose [8]. Ethanol is well-suited as a solvent because it can degrade cell walls, making bioactive compounds more easily released from plant cells, and the addition of ethanol to the soda solution can improve the selectivity of the reaction towards lignin [9]. Ethanol solvent is used because it breaks the α-ether bonds between lignin and cellulose, making lignin soluble [8].

Based on the research by Irawan, the addition of ethanol in the MCO₂ process not only increases the degradation or removal of lignin but also plays a role in minimizing fiber degradation, as illustrated by the viscosity values produced in the MCO₂ process [10]. Therefore, from the above background, the author conducted a study titled "The Addition of Ethanol as a Lignin Extractor to Reduce NaOH Consumption and Fiber Degradation in the MCO₂ Stage." This research aims to determine the most optimal proportion of ethanol and NaOH through the analysis of kappa number, brightness, and viscosity test results, which can illustrate the extent of fiber degradation in the pulp. It also aims to identify the effects of temperature and reaction time variations on kappa number, brightness, and viscosity, and to analyze the impact of ethanol addition on NaOH consumption and pulp quality in the MCO₂ stage.

**METHOD**

**Materials**

The materials needed in this research were pulp taken from the outlet of washpress 3 in the Fiberline Department, the chemicals NaOH and ethanol, as well as demineralized water used in the process of diluting the pulp to reach a consistency of 10%.

**Sample Preparation and Treatments**

The raw material used is pulp that has undergone cooking, screening, and washing processes. The pulp is taken from washpress 3, after the sampling consistency (TAPPI T240 om-02), kappa number (TAPPI T236-99), viscosity (TAPPI T230-04), and brightness testing (TAPPI T 452-18).

Pulp samples taken from wash press 3 are placed into an 80 mesh screen and washed with demineralized water until free from black liquor mixture. The washed samples are dried using a dehydrator until dry. Once dry, the samples are disintegrated until there are no lumps in the pulp. The washed pulp samples undergo consistency testing to determine the amount of water contained in the pulp sample. After determining the pulp consistency, calculations are performed to determine the amount of pulp to be used if cooking with 70 grams of OD.

Once determined, the pulp is weighed using plastic. Then, the weighed pulp samples are mixed with chemicals Ethanol and NaOH according to the predetermined proportions, which are 100%:0%, 90%:10%, 80%:20%, 70%:30%, 60%:40%, 50%:50%, 40%:60%, 30%:70%, 20%:80%, 10%:90%, and 0%:100%. Demineralized water is then added until the consistency reaches 10%. After that, the pulp samples injected with chemicals and water are homogenized and tied using rubber bands.

Once homogenized and sealed, the samples are placed into a water bath set at a temperature of 80°C, for optimal dosage variations using temperature variations of 80°C, 85°C, 90°C, and 95°C. When the temperature has stabilized at the desired level, the reaction time is calculated for 80 minutes, for optimal dosage variations, the reaction time used is 70 minutes, 75 minutes, 80 minutes, 85 minutes, and 90 minutes.

After the reaction time is completed, the pulp samples are removed from the water bath, and the pulp is separated from the filtrate or black liquor using an 80 mesh screen by squeezing. The separated filtrate is checked for pH, while the reacted pulp is
washed using demineralized water. After the pulp is free from the black liquor mixture, it is dried using a dehydrator. Once dry, the pulp is disintegrated until no lumps remain. The pulp can then proceed to consistency (TAPPI T240 om-02), kappa number (TAPPI T236-99), viscosity (TAPPI T230-04), and brightness testing (TAPPI T 452-18).

RESULT AND DISCUSSION
Characterization of Raw Materials
The raw materials used in this study are divided into two categories, namely pulp raw materials and chemicals. The pulp raw materials used in the dosage and temperature variations were taken on different days than the pulp raw materials used in the reaction time variations, so the initial characteristics testing of the pulp raw materials was conducted twice, including consistency, kappa number, viscosity, and brightness testing. Meanwhile, to determine the initial characteristics of the chemicals used, pH and concentration testing were conducted. Here are the results of the initial characteristics testing of the raw materials.

Table 1. Initial Characteristics of Pulp Raw Materials in Dose and Temperature Variations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consistency</td>
<td>%</td>
<td>29</td>
</tr>
<tr>
<td>Kappa Number</td>
<td></td>
<td>22,15</td>
</tr>
<tr>
<td>Viscosity</td>
<td>(cP)</td>
<td>1179,09</td>
</tr>
<tr>
<td>Brightness</td>
<td>% ISO</td>
<td>26,75</td>
</tr>
</tbody>
</table>

Table 2. Initial Characteristics of Pulp Raw Materials in Reaction Time Variations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consistency</td>
<td>%</td>
<td>30,32</td>
</tr>
<tr>
<td>Kappa Number</td>
<td></td>
<td>19,75</td>
</tr>
<tr>
<td>Viscosity</td>
<td>(cP)</td>
<td>1054,31</td>
</tr>
<tr>
<td>Brightness</td>
<td>% ISO</td>
<td>30,32</td>
</tr>
</tbody>
</table>

Table 3. Initial Characteristics of Chemical Raw Materials

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Concentration</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium Hydroxide</td>
<td>434,30 g/l</td>
<td>14,7</td>
</tr>
<tr>
<td>Ethanol</td>
<td>99,7 %</td>
<td>8,5</td>
</tr>
</tbody>
</table>

Method of Cooking Pulp Samples Using NaOH Chemicals and Analysis of Pulp Testing Results
Cooking pulp samples using NaOH chemicals without the addition of ethanol was conducted to compare the quality of the pulp produced before and after the addition of ethanol, as well as to determine the extent to which the addition of ethanol can reduce NaOH consumption. The test results are used as the target to be achieved in this study. In the cooking process, NaOH added to the pulp sample was 20 kg/ADT, then demineralized water was added to reach a consistency of 10%. After that, it was homogenized and placed in a water bath at a temperature of 80°C for a reaction time of 80 minutes. After the cooking process was completed, the pulp was tested for kappa number, viscosity, and brightness. Here are the test results of the pulp in the cooking process using NaOH chemicals, which are used as the target of this study.

Table 4. Target Parameters in Dose and Temperature Variations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kappa Number</td>
<td>≤ 17,6</td>
</tr>
<tr>
<td>Viscosity</td>
<td>≥ 1050,71 cP</td>
</tr>
<tr>
<td>Brightness</td>
<td>≥ 32,10 % ISO</td>
</tr>
</tbody>
</table>

Table 5. Target Parameters in Reaction Time Variations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kappa Number</td>
<td>≤ 15,8</td>
</tr>
<tr>
<td>Viskositas</td>
<td>≥ 1017,46 cP</td>
</tr>
<tr>
<td>Brightness</td>
<td>≥ 32,66 % ISO</td>
</tr>
</tbody>
</table>

Cooking Process with Various Proportions of Ethanol and NaOH and Analysis of Pulp Testing Results
Cooking in dose variations using various proportions of ethanol and NaOH (shown in table 6). After adding the chemicals, demineralized water was added to reach a consistency of 10%, and cooked in a water bath at a temperature of 80°C for a reaction time of 80 minutes. After the cooking process, testing was conducted for kappa number, viscosity, and brightness.
Here are the proportions of ethanol and NaOH used in the dose variations.

**Table 6. Chemical Charge in Dose Variations**

<table>
<thead>
<tr>
<th>Proportions of Ethanol and NaOH</th>
<th>Chemical Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Etanol (Kg/ADT)</td>
</tr>
<tr>
<td>Blank</td>
<td>0</td>
</tr>
<tr>
<td>Target Achievement (NaOH 100%)</td>
<td>0</td>
</tr>
<tr>
<td>100:0%</td>
<td>20</td>
</tr>
<tr>
<td>90:10%</td>
<td>18</td>
</tr>
<tr>
<td>80:20%</td>
<td>16</td>
</tr>
<tr>
<td>70:30%</td>
<td>14</td>
</tr>
<tr>
<td>60:40%</td>
<td>12</td>
</tr>
<tr>
<td>50:50%</td>
<td>10</td>
</tr>
<tr>
<td>40:60%</td>
<td>8</td>
</tr>
<tr>
<td>30:70%</td>
<td>6</td>
</tr>
<tr>
<td>20:80%</td>
<td>4</td>
</tr>
<tr>
<td>10:90%</td>
<td>2</td>
</tr>
</tbody>
</table>

**Analysis of Optimal Proportions**

The determination of the most optimal proportion is based on the kappa number, brightness, and viscosity values produced in the pulp cooking process. A low kappa number and high brightness indicate a low lignin content in the pulp, which is one of the success parameters of the delignification process. Therefore, the lower the kappa number and the higher the brightness, the more optimal the delignification process of that proportion. However, viscosity values must also be considered and must meet the desired target in the study because high viscosity will result in pulp with good physical resistance properties.

**Cooking Process with Temperature and Reaction Time Variations and Testing the Pulp Results**

The most optimal proportions of ethanol and NaOH are used in cooking for temperature and reaction time variations. In the temperature variation, temperatures of 80°C, 85°C, 90°C, and 95°C are used with a reaction time of 80 minutes and a consistency of 10%. In the reaction time variation, times of 70 minutes, 75 minutes, 80 minutes, 85 minutes, and 90 minutes are used with a constant temperature of 80°C and a consistency of 10%. After cooking is completed, testing is conducted for kappa number, viscosity, and brightness. Then, the results obtained are compared with the target values to be achieved.

**Testing of Kappa Number on Dose Variations**

The Kappa number for all dose variations decreased compared to the blank, indicating lignin degradation in the pulp. Delignification occurs because ethanol and NaOH have the ability to degrade and dissolve lignin [8]. Based on figure 1, the graph shows that the kappa number begins to decrease at ethanol and NaOH proportions of 100:0%, 90:10%, 80:20%, 70:30%, 60:40%, and 50:50%, with values of 19.75, 19.65, 18.6, 18.5, 18.2, and 18 respectively. However, the kappa number increases again at ethanol and NaOH proportions of 40:60%, 30:70%, 20:80%, and 10:90%, with kappa numbers of 18.1, 18.25, 18.45, and 18.5 respectively. The decrease in kappa number is partly influenced by the solubility of NaOH in ethanol [11]. On the other hand, the increase in the kappa number is due to the property of ethanol that can evaporate at high temperatures, thereby reducing the solubility of lignin [12].

![Figure 1. Test Results of Kappa Number on Dose Variations](image_url)

In this study, the target kappa number to be achieved is 17.6. Based on figure 1, the graph shows that the kappa number values for all variations of ethanol and NaOH doses have not yet reached the target set. However, from all the variations, an optimum dose proportion between ethanol and NaOH was found to be 50:50%, which has the lowest kappa number value of 18. In the delignification process, a low kappa number
number indicates a low lignin content in the pulp, which is one of the success parameters of the delignification process.

**Viscosity Test Results on Dose Variations**

The viscosity of pulp in all variations of ethanol and NaOH doses after cooking decreased compared to the blank. The decrease began at ethanol and NaOH proportions of 100:0%, 90:10%, 80:20%, 70:30%, 60:40%, 50:50%, down to 40:60%, with viscosities of 1091.77 cP, 1091.39 cP, 1081.61 cP, 1079.04 cP, 1072.65 cP, 1068.11 cP, and 1058.44 cP, respectively. However, at the ethanol and NaOH proportion of 30:70%, there was an increase in viscosity. The increase in viscosity occurred from the ethanol and NaOH proportions of 30:70%, 20:80%, and 10:90%, with viscosities of 1068.11 cP, 1107.86 cP, and 1109.92 cP, respectively. The decrease or increase in viscosity is also influenced by the delignification process and the kappa number value. Increased delignification and reduced kappa number lead to higher pulp degradation, resulting in the production of pulp with higher fine fiber fragmentation and lower viscosity [13]. The higher the viscosity, the higher the kappa number.

**Figure 2. Viscosity Test Results for Dose Variations**

The target viscosity to be achieved is ≥1050.71 cP. Based on Figure 2, the graph shows that the viscosity values for all variations of ethanol and NaOH doses have met the target. The addition of ethanol in the delignification process can increase the viscosity value, but this is also influenced by the kappa number value obtained, as the increase and decrease in viscosity are directly proportional to the kappa number value. The higher the kappa number value produced, the higher the viscosity value, which is an effect of the suboptimal reaction during the delignification process [14]. At the optimum ethanol and NaOH proportion of 50:50%, the viscosity value obtained was 1068.11 cP. This indicates that the cellulose condition in the delignification process at that proportion is still good compared to the magnitude of the kappa number decrease.

**Brightness Test Results on Dose Variations**

The increase in brightness occurred for all dose variations compared to the blank (Figure 3). The increase in brightness began at ethanol and NaOH proportions of 100:0%, 90:10%, 80:20%, 70:30%, 60:40%, and 50:50%, with brightness values of 27.53% ISO, 28.93% ISO, 30.92% ISO, 31.41% ISO, 31.43% ISO, and the highest being 32.15% ISO. After the 50:50% proportion, the brightness values decreased again at ethanol and NaOH proportions of 40:60%, 30:70%, 20:80%, and 10:90%, with brightness values of 32.08% ISO, 32.01% ISO, 31.92% ISO, and 31.64% ISO, respectively. The increase in brightness is due to the reduced lignin content in the pulp, indicated by a lower kappa number. The lower the kappa number, the higher the brightness value, as lignin affects the brightness of the pulp.

**Figure 3. Brightness Test for Dose Variations (%ISO)**

This study did not use the bleaching process, so the resulting brightness is purely due to the changes in the proportion of ethanol and NaOH used. The highest brightness value in the ethanol and NaOH dose variations was at the 50:50% proportion, which was 32.15% ISO. This value meets the target parameter of ≥32.10% ISO.

**Kappa Number Test Results on Temperature Variations**
The increase in temperature results in a decrease in the kappa number obtained. This can be seen in figure 4 where the temperature and kappa number values are inversely proportional. The kappa numbers at the temperature variations of 80°C, 85°C, 90°C, and 95°C are 18, 17.3, 17.1, and 16.6 respectively. The highest kappa number is at the temperature variation of 80°C, which is 18, while the lowest kappa number occurs at 95°C with a kappa number of 16.6. The increase in temperature significantly decreases the kappa number because, as the cooking temperature increases, the reaction rate tends to increase, and the lignin dissolution process also becomes faster [16]. According to another reference, the faster the lignin dissolution, the more lignin will degrade, resulting in less lignin remaining [17].

Increasing the temperature by 5°C for each variation is very effective in reducing the kappa number in pulp. The kappa number obtained exceeds the target desired for cooking using 100% NaOH. Variations of 85°C, 90°C, and 95°C have met the target, which is ≤17.6.

**Figure 4. Results of Kappa Number Temperature Variations**

**Viscosity Test Results for Temperature Variations**

Based on the experiment, it is shown that the higher the cooking temperature, the lower the viscosity, due to many macromolecular compounds (cellulose, hemicellulose, and lignin) that are dissolved in the cooking solution (figure 5). The highest viscosity is at the temperature variation of 80°C with a value of 1068.11 cP. Then the viscosity continues to decrease at temperatures of 85°C, 90°C, and 95°C with viscosities of 1056.78 cP, 1049.25 cP, and the lowest at 1034.49 cP respectively.

The target viscosity to be achieved based on cooking using 100% NaOH is ≥1050.71. The temperature variations that meet the target are 80°C and 85°C, while the viscosity at 90°C and 95°C does not yet meet the target. In the delignification process, fiber conditions will experience a decrease in quality (degradation) as a result of the process conditions themselves. This degradation, in turn, will cause the fibers to break as a result of the influence of heating and the nature of the chemicals used. The results obtained are in line with the Arrhenius equation, which states that the higher the reaction temperature, the higher the delignification rate constant. High temperatures cause more lignin to degrade. However, on the other hand, polysaccharides also degrade in large quantities [18].

**Figure 5. Viscosity Results of Temperature Variations**

**Brightness Test Results for Temperature Variations**

The brightness value of the pulp increases with increasing cooking temperature (figure 6). At temperature variations of 80°C, 85°C, 90°C, and 95°C, the brightness values achieved are 32.15% ISO, 32.56% ISO, 32.77% ISO, and 33.02% ISO, respectively. The higher the delignification rate, the higher the brightness of the pulp. Dark color in pulp is generally caused by lignin, which is one of the main components of wood and is classified as a phenolic compound that is highly prone to oxidation [19]. The brightness values at all temperature variations have met the target of ≥32.10% ISO. Increasing the cooking temperature is very effective in optimizing the brightness value.
Kappa Number Test Results for Reaction Time Variations

Based on the experiment, the kappa numbers obtained for reaction time variations of 70 minutes, 75 minutes, 80 minutes, 85 minutes, and 90 minutes are 16.4, 16.1, 15.95, 15.8, and 15.6 respectively. Increasing the reaction time can decrease the kappa number in pulp; the longer the reaction time, the lower the kappa number (figure 7). The highest kappa number is at the 70-minute reaction time variation, which is 16.4, while the lowest kappa number is at the 90-minute reaction time variation, which is 15.6.

A long reaction time results in more frequent interactions between lignin molecules and the cooking liquid, causing more dissolved lignin and lower lignin content obtained. The longer the cooking time used, the lower the kappa number obtained. Conversely, if a shorter cooking time is used, the kappa number produced will be higher because the lignin breakdown process is not yet complete [20].

The target kappa number to be achieved from cooking using 100% NaOH with a reaction time of 80 minutes is ≤15.8, so the reaction time variations of 70 minutes, 75 minutes, and 80 minutes do not meet the target because the kappa number obtained is higher than the target. Meanwhile, the kappa number that meets the target is found in the reaction time variations of 85 minutes and 90 minutes. The quality parameter of pulp in terms of kappa number in cooking using 100% NaOH can be achieved if the addition of ethanol and NaOH in a 50:50 proportion is done with an increased reaction time to 85 minutes or 90 minutes to maximize the delignification process.

Viscosity Test Results for Reaction Time Variations

The experimental results show that the viscosity for reaction time variations of 70 minutes, 75 minutes, 80 minutes, 85 minutes, and 90 minutes are 1049.56 cP, 1042.22 cP, 1030.80 cP, 1025.20 cP, and 1023.04 cP, respectively. This decrease in viscosity is caused by the fibers in the pulp becoming more degraded (figure 8). Increasing the reaction time causes the delignification rate to increase, but this increase in delignification also leads to higher pulp degradation, resulting in pulp with higher levels of fine fiber fragmentation and lower viscosity [13].

The highest viscosity is at the 70-minute reaction time, which is 1049.56 cP. The lowest viscosity is at the 90-minute reaction time variation, which is 1023.04 cP. The target viscosity to be achieved is ≥1017.46, which indicates that the viscosity values for the reaction time variations of 70 minutes, 75 minutes, 80 minutes, 85 minutes, and 90 minutes meet the target. Increasing the reaction time can increase the delignification rate while still maintaining cellulose degradation in the pulp.

Brightness Test Results for Reaction Time Variations

The experimental results show that for reaction times of 70 minutes, 75 minutes, 80 minutes, 85 minutes, and 90 minutes, the brightness values increase successively to 31.89% ISO, 31.99% ISO, 32.34% ISO, 32.46% ISO, and reaching the highest value
of 32.69% ISO. The target brightness to be achieved for the reaction time variations is 32.66% ISO. However, the 70-minute, 75-minute, 80-minute, and 85-minute reaction time variations resulted in pulp with brightness below the target, while the 90-minute reaction time variation resulted in pulp brightness higher than the target (figure 9).

**Figure 9.** Brightness Results for Reaction Time Variations

A 50%:50% proportion of ethanol and NaOH can only achieve the brightness value obtained from cooking using 100% NaOH if the cooking time of the pulp is extended to 90 minutes. The less residual lignin, the higher the brightness value, or the more lignin is delignified, the higher the brightness value will be [15].

**CONCLUSION**

From the research conducted, several conclusions can be drawn. The most optimal variation of ethanol and NaOH dosage occurs at a 50%:50% proportion, resulting in a kappa number of 18, viscosity of 1067.67 cP, and brightness of 32.15% ISO. As the temperature and reaction time increase, the pH value, kappa number, and viscosity decrease, while the brightness increases.

In the 50%:50% ethanol and NaOH dosage proportion, the best temperature is 85°C, with a kappa number of 17.3, viscosity of 1056.78 cP, and brightness of 32.15% ISO. Meanwhile, the best reaction time is 90 minutes, with a kappa number of 15.6, viscosity of 1023.04 cP, and brightness of 32.69% ISO. Ethanol cannot replace 100% NaOH, NaOH can only be reduced by 50%. To achieve better kappa number, viscosity, and brightness than using 100% NaOH, the temperature must be increased to 85°C or the reaction time must be extended to 90 minutes.

Suggestions for future research include further studies on the optimal dosage variations combined with oxygen and tested in two stages, similar to field conditions. It is also necessary to check pulp yield and use a microscope along with calculating the degree of polymerization to further understand fiber degradation. Additionally, further research is needed on the increase in temperature regarding energy usage and industrial costs.

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**REFERENCES**


