



# Article Evaluation of Polyurethane Foam Derived from the Liquefied Driftwood Approaching for Untapped Biomass

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**Abstract**: Nowadays, climate change has become a serious concern, and more attention has been drawn to utilizing biomass sources instead of fossil sources and how petroleum chemical plastics should be reduced or replaced with bio-based materials. In this study, the optimized condition of liquefaction of driftwood was examined. There was a concern that driftwood might have some decay and chemical change. However, according to the Organic Micro Element Analyzer (CHN analyzer) test and Klason lignin and Wise methods, the results proved that lignin content (37.5%), holocellulose content (66.9%), and CHN compositions were very similar to regular wood. The lowest residue content of bio-polyols was produced using liquefaction conditions of 150 °C, reaction time of 180 min, catalyst content of 10% w/w, and 12.5% w/w driftwood loading. Polyurethane foam (PUF) derived from the liquefaction of driftwood and bio-based cyanate was prepared. The PUF prepared from the liquefaction of the driftwood exhibited slightly decreased thermal durability but was superior in terms of 3-time faster biodegradation and 2.8-time increased water adsorption rate compared to pure petroleum-based PUF. As a result, it was shown that driftwood can be identified as a biomass resource for biodegradable PUF.

Keywords: liquefaction; driftwood; bio-polyol; polyurethane foam; biodegradation; water absorption



In recent years, it has become increasingly common to discuss the reduction in global CO<sub>2</sub> emissions and the use of alternative fossil resources in the face of climate change. Since the Paris Agreement and the United Nations' Sustainable Development Goals (SDGs), various countries have kept making efforts to achieve a carbon-neutral and sustainable society, but still more measures are needed to tackle this challenge.

In this light, there has been more interest and research into biomass as a resource that captures and utilizes  $CO_2$  [1]. It is widely recognized that optimized use of these sustainable resources is the most important technology for achieving a carbon-neutral society [2].

Not only wood but also biomass resources, such as abundant biomass, which have never been utilized before, are drawing much attention. The utilization of nonedible biomass is especially recognized as a key to realizing a sustainable society. These resources offer not only significant quantities but also potential cost advantages. Hence, there is much research on these kinds of resources currently. For instance, research on rice straw [3], food waste [4], jatropha biomass [5], and forest residue was investigated. In our laboratory, previously, the utilization of cotton stalks [6] and other biomass resources was researched [7,8]. With this background, the current study focuses on driftwood as an untapped biomass resource [9,10]. Driftwood is mainly generated through landslides caused by heavy rain. These woods end up in the river and float downstream. Then, the uncollected driftwood turns into waste. Once forest resources become driftwood



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**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). waste from a natural disaster, they need substantial efforts and time to be collected and disposed of.

It is reported that currently, the annual amount of driftwood in Japan is about 90,000 Mg to 300,000 Mg [9]. If these abundant wood materials can be utilized in applications, they become a biomass resource with the potential to replace a large amount of fossil sources. Moreover, the amount of driftwood that is generated has been closely linked to global warming phenomena. It is shown that excess greenhouse gas emissions aided the progression of global warming and, as such, led to increased typhoon intensity, frequency, and the amount of rainfall related to it. This means that not only the chances but the scale of these events have been growing larger each year, exemplified by recent reports of natural disasters and river flooding. As the occurrence of these natural disasters contributes to the generation of driftwood, concerns grow even larger when taking into consideration future climate changes. Consequently, it is necessary to come up with solutions to utilize driftwood in response to these climate challenges.

However, the current applications of driftwood are very limited. For instance, it may be used as biofuel, wood chips for gardening, and aquarium driftwood. The reason for the limited applications of driftwood is that low durability and changes in the condition due to rotting are very concerning. Driftwood is affected by progressive decay and increasing salt content while soaking in seawater or river water during the long process of its generation. The decay leads to physical and chemical changes, resulting in decreased strength and quality of the wood. On the other hand, high salt content can cause soil pollution with NaCl. Hence, driftwood is not utilized as timber, and most of it ends up burned and used as fuel. In addition, although driftwood has the potential to be a significant source of biomass resource, the locations and timing of the occurrence cannot be predicted, making the collection process very costly. Local governments in Japan provide the collected driftwood to people for free instead of paying the cost of disposing of it.

Therefore, driftwood is certainly a biomass resource, but it is very tough to utilize due to its generation process and characteristics. To resolve this problem, this study focused on examining the potential of driftwood use and the conversion of driftwood to make a biodegradable plastic [11,12]. Out of various possibilities of utilization for biodegradable plastic, this study investigated the optimized liquefaction process [13–15] of driftwood to make polyurethane foam (PUF) [16]. Currently, most products in the large PUF market are synthesized with oil in order to produce large quantities and maintain high quality. However, there is a large number of existing studies exploring how to replace the oil in PUF with biomass resources [17–21]. On the other hand, the number of research on PUF derived from driftwood is very limited. In this study, optimizing the liquefaction processes for the driftwood and beyond carrying out the production of foam, the characteristics of the foam produced, such as biodegradability in soil and thermal properties, were compared to those of petroleum-based foam. Discovering the advantages of biobased PUF can stimulate a more widespread use of the product for a variety of applications in the future. In Figure 1, this work's graphical abstract is shown.



Figure 1. Concept of liquefied driftwood approaching for untapped biomass.

# 2. Materials and Methods

2.1. Materials

Driftwood was collected in wet conditions near the Nakazato River in Aomori Prefecture. It was determined that there were various types of wood among the driftwood samples.

For component analysis, several samples were taken, and all of them were mixed to create a driftwood sample for the liquefaction experiment.

Additives used in the polyurethane foaming process included the cyanate resin, STABIO (D-370N; Mitsui Chemicals, Tokyo, Japan), the chemical structure shown in Figure 2, silicone surfactant (VORASURF SH193; Toray Dow Corning Silicone, Ind. Ltd., Tokyo, Japan), and dibutyltin dilaurate (DBTDL; Wako Pure Chemicals, Ind. Ltd., Japan). DBTDL is a well-known cure catalyst for polyurethane foam. All other reagents were of analytical grade (Wako Pure Chemicals, Ind. Ltd., Osaka, Japan). All chemicals used in this study were reagent grade and used without further purification.



Figure 2. The chemical structure of STABIO D-370N.

#### 2.2. Preparation of Driftwood Meal

To obtain wood meal samples below 250  $\mu$ m, the following procedure was carried out. The original driftwood was cut using a saw and then ground with a blender mixer. A fine wood meal sample of 250  $\mu$ m in size was obtained using an impact grinder with a 250  $\mu$ m mesh. The samples were then defatted through Soxhlet extraction at 110 °C for 6 h. For the defatting process, a total of 50 mL of ethanol and 100 mL of benzene were used. After the



6-h Soxhlet extraction, the woody sample was vacuum-filtered and thoroughly dried in an oven.

The process of experiments in this study is shown in Figure 3.

Figure 3. Processes of experiments in this study.

#### 2.3. Estimating the Content of Lignin and Holocellulose (Klason Lignin and Wise Method)

The content of lignin and holocellulose was measured following the same method as a previous study [22].

Analysis of the content ratio of lignin was performed by the Klason lignin method. A total of 1.0 g of the defatted wood sample and 15 mL of the 72% sulfuric acid were put in a 50 mL beaker and mixed for four hours, stirring occasionally. These contents were poured into a 1 L flask, which was filled with 560 mL of extra-pure water. This flask was fitted with a condenser and heated at 110 °C in an oil bath for four hours. These contents were then filtered using a glass filter (1GP16, AS ONE Co., Ltd., Osaka, Japan) and rinsed with hot water and pure water. The residual solid was lignin.

Analysis of the content ratio of holocellulose was performed by the Wise method. A 2.5 g of the defatted woody samples was put in a 300 mL flask with 150 mL of pure water, 1.0 g of sodium chlorite, and 0.20 mL of acetic acid, then heated at 75 °C in a water bath, with occasional stirring; 1.0 g of sodium chlorite and 0.2 mL of acetic acid were added three times at four-hour intervals; then, these contents were filtered using a glass filter (1GP100, AS ONE Co., Ltd., Osaka, Japan) and rinsed with pure water and acetone. The residual solid left was holocellulose.

# 2.4. Elemental Analysis of Driftwood Using CHN Analyzer

To analyze the organic components of the driftwood, we measured the components using an Organic Micro Element Analyzer (CHN analyzer; MT-5 Yanaco Co., Ltd., Tokyo, Japan), with temperatures set at 950 °C for Combustion Furnace, 850 °C for Oxidation Furnace, and 550 °C for Reduction Furnace, using helium as the carrier gas. In this study, antipyrine was used as the standard sample [23].

# 2.5. Liquefaction of Driftwood

In a 500 mL three-neck reaction flask equipped with a stirrer and a reflux condenser, we added 10 g of driftwood meal and 60 g of the mixed solvent, as specified in Table 1. The reaction flask was then placed in a preheated oil bath at three different temperatures:

140 °C; 150 °C; and 160 °C. The reaction was initiated by adding the catalyst ( $H_2SO_4$ ) to the reaction flask. After liquefaction times of 15 min, 30 min, 90 min, 180 min, and 300 min, the liquefied woody samples were collected and placed in a weighted vial for residue analysis. To stop the liquefaction reaction, the vial was immersed in cold water. All liquefaction conditions considered in this study are shown in Table 1.

Table 1. Liquefaction conditions.

Solvent	Polyethylene Glycol: Glycerin = 9:1, 8:2, 7:3 by Weight				
Material Ratio	Driftwood: Solvent = 1:6, 1:7, 1:8 by weight rate				
Reaction Time	300 min maximum				
Temperature	140 °C, 150 °C, 160 °C				

#### 2.6. Characterization of the Liquefied Driftwood

To assess liquefaction, the functional groups of the liquefied driftwood samples were analyzed using Fourier transform infrared spectroscopy (FT-IR) (JASCO Co., Ltd., Tokyo, Japan). Thinly clipped liquefied driftwood samples were placed between potassium bromide plates, and the resulting pellet was inserted into the FT-IR instrument to measure the functional groups [24].

For residue measurement, 10 mL of methanol was added to the vial and thoroughly mixed. Filtration was performed using a vacuum pump and paper filters (ADVANTEC C5, Toyo Roshi Kaisha, Ltd., Tokyo, Japan). The filtered residue was then dried for 24 h in an oven at 105 °C. The residue rate was calculated according to Equation (1).

ratio of residue (%) = 
$$W1/W0 \times 100$$
 (1)

where W1 is the weight ratio of residue in the taken liquefied sample; W0 is the weight ratio of driftwood in the initial sample.

#### 2.7. Preparation of Polyurethane Foam (PUF)

Table 2 shows PUF production conditions in this study. The expression in sample name PEG400 or LW1:7 shows the polyols used to prepare the polyurethane foam. PEG400 is a purchased polyethylene glycol (petroleum-based), and LW1:7 is a liquefied driftwood of solvent ratio 1:7 by weight. Non-residue is a filtered sample to remove residue. [NCO]/[OH] is the mixture ratio of functional groups of isocyanate and hydroxyl groups. Number 1 indicates that the number of these groups is equal.

		Isocyanate Polyol [g]		DBTDL	Silicone Oil	Water	
	[NCO]/[OH]	[g]	PEG400	LW	[g]	[g]	[g]
PUF-PEG400	1	30	15	-	1.5	1.0	1.0
PUF-LW1:7 (non-residue)	1	25	-	15	1.0	1.0	1.0
PUF-LW1:7	1	25	-	15	1.0	1.0	1.0

Table 2. Polyurethane foam production conditions.

After applying a release agent to a paper cup, liquefied driftwood samples or polyethylene glycol (PEG)400 were mixed with ultra-pure water and silicone oil for 2 min at a stirring speed of 1000–1200 rpm. Then, biobased cyanate resin, STABIO D-370N, and the cure catalyst, a dibutyltin dilaurate (DBTDL), were added to the cup and stirred for an additional 2 min at 2000 rpm. To cure the mixed resin, the samples were left at room temperature in a free-standing position for 2 days. After the curing process, the samples were removed from the cup, and their properties were evaluated.

### 2.8. Scanning Electron Microscopy (SEM) of PUF

To examine the cell size and shape of PUF, scanning electron microscopy (SEM) was performed using SU1510 at the Comprehensive Analysis Center for Science, Saitama University (HITACHI High-Tech, Tokyo, Japan). The images were observed with Au-Pd sputter coating. The coating will help prevent electrical charging for SEM. The applied voltage was 15 kV, and the observation magnification was 100 times zoom.

#### 2.9. Measurement of Water Absorption Rate of PUF

The water absorption test was conducted according to Japanese Industrial Standards K7209 [25]. Sample weights were measured precisely using an electric balance, and the water absorption rate was calculated using the formula (2) shown below.

Water Absorption Rate (%) = 
$$\frac{(m_2 - m_1) + (m_1 - m_3)}{m_1} \times 100$$
 (2)

 $m_1$ : the sample weight before water soaking (mg);  $m_2$ : the sample weight after water soaking (mg);  $m_3$ : the sample weight after drying (mg).

#### 2.10. Thermal Decomposition

To evaluate the thermal decomposition characteristics of polyurethane foams, simultaneous thermogravimetry and differential thermal analysis (TG-DTA) were performed using a TG-DTA device (DTG-60, Shimadzu Corporation, Kyoto, Japan). The thermal behavior of polyurethane foam is important because foam is mainly used as a thermal insulator. The measurements were carried out with a ramp speed of  $10 \,^\circ C \cdot \min^{-1}$  in ambient air [26].

#### 2.11. Biodegradability of PUF

Cured PUFs were cut into pieces measuring  $12 \text{ mm} \times 12 \text{ mm} \times 12 \text{ mm}$ , and their weights were measured using an electric balance. Subsequently, the specimens were placed in a plastic container with 2 cm of soil from the garden of Saitama University and covered with additional soil to fully embed the specimens. Each foam sample had three specimens, resulting in a total of nine embedded specimens. The plastic container was placed in an artificial weather chamber maintained at 25 °C, 60% moisture level, with continuous lighting for 24 h. The samples were excavated at monthly intervals, and the soil was washed with distilled water, sonicated for 20 min, and then dried at room temperature for at least two days. The weights were measured, and the weight loss rate of the PUF before and after embedding was calculated using the following Equation (3). The average weight loss for each type of sample was determined based on the average of the three specimens.

Weight loss rate(%) = 
$$\frac{w_3}{w_4} \times 100$$
 (3)

 $w_3$ : the foam weight before embedding (g);  $w_4$ : the foam weight after embedding (g).

#### 3. Results and Discussion

## 3.1. Componential Analysis of Driftwood

The results of the componential analysis were as follows: carbon (C) 46%; hydrogen (H) 6%; and oxygen (O) 48%. These values were similar to those of timber wood, which had carbon (C) 50%, hydrogen (H) 6%, and oxygen (O) 44%. Therefore, there was no significant difference between driftwood and timber wood. Although there were concerns about changes in the elemental composition of driftwood during the weathering process, the obtained results showed almost identical compositions. This result suggested that the driftwood samples in this study were not exposed to water or a biodegradable environment

for a long period of time. Wood normally shows degradation after a couple of years. Thus, it was estimated that the driftwood used came from the upside forest within a year.

Using the Wise method and Klason lignin analysis, the amounts of holocellulose and lignin were determined to be 66.92% and 37.54%, respectively. The lignin content in driftwood depends on whether it is softwood or hardwood, with softwood typically containing 25–35% lignin and hardwood containing 18%-25% lignin. Generally, softwood has 7–10% more lignin than hardwood [27]. Based on these values, the driftwood obtained in this study appeared to be from softwood, which suggests that the collection site for the driftwood was in a softwood forest.

# 3.2. Evaluation of Liquefied Driftwood

#### 3.2.1. Structural Characteristics of the Liquefied Driftwood [28,29]

The Fourier transform infrared spectroscopy (FT-IR; Jasco Co., Ltd., Japan) absorption spectra of the liquefied driftwood are shown in Figure 4. Indicated mix solvent is the spectra of only solvent. A peak at 1725 cm<sup>-1</sup> was observed in the liquefied driftwood but was not observed in the solvent alone. This peak corresponds to the C=O stretching vibration and is due to the carbonyl stretching of cellulose decomposition or hemicellulose. In addition, the peak at 820 cm<sup>-1</sup> can be assigned to the C-H out-of-plane bending vibration of aromatic compounds from the driftwood. These peaks obtained from the liquefied driftwood were based on cellulose or lignin-derived decomposition compounds. Therefore, this indicates that the liquefaction process of the driftwood was completed.



Figure 4. FT-IR spectrum of liquefied driftwood.

3.2.2. Optimization of the Driftwood Liquefaction Process

In this study, the optimization of liquefaction process efficiency was carried out based on the residue content [30]. The parameters considered for optimization included reaction temperature, reaction time, composition ratio of the mixed solvent, and volume ratio of the mixed solvent to driftwood meal.

Figure 5 illustrates the variation in residue content as a function of changing reaction temperature and reaction time. Specifically, the residue content at reaction temperatures of 140 °C, 150 °C, and 160 °C were investigated, respectively. Irrespective of the reaction temperatures, a rapid liquefaction process occurred within the first 15 min. At reaction temperatures of 140 °C and 150 °C, the residue content decreased with increasing reaction time. For a reaction time of 300 min, the residue content was 32.0% at 140 °C and 27.6% at 150 °C.



Figure 5. Comparison of residue content by liquefaction temperature.

Conversely, during the 160 °C reaction, the residue content decreased until 180 min but subsequently increased by approximately 10% between 180 min and 300 min. This observation suggests the occurrence of recondensation of lignin and low-molecular-weight sugars. At high-temperature reactions, both the liquefaction process and recondensation reaction are accelerated, consequently influencing the residue content.

The results of the variation in the mixed solvent polyethylene glycol (PEG) 400 and glycerol are shown in Figure 6.



Figure 6. Comparison of residue content by mixed solvent.

Glycerol acts as an inhibitor of the recondensation reaction that occurs simultaneously with the liquefaction reaction. By reducing the recondensation reaction, it is possible to enhance the biomass content in the final liquefied driftwood.

In this study, the mixing ratios of PEG 400 to glycerol set at 9:1, 8:2, and 7:3 were examined. For the 9:1 ratio, the residue content was approximately 40% after a 300-min reaction,

but for the 7:3 ratio, it decreased to 22.8%. As mentioned previously, it appeared that the addition of more glycerol prevented recondensation and accelerated the depolymerization of lignin and cellulose. Lower residue content in this study indicated higher liquefaction efficiency, leading us to identify the optimal mixing ratio of PEG 400 to glycerol as 7:3.

For the last parameter of considerations, the volume ratio of the mixed solvent to the driftwood meal setting at a temperature of 150 °C, mix ratio 7:3, and acid catalyst 10% w/w were examined. The result of the volume ratios 7:1, 6:1, and 5:1 is shown in Figure 7. As a sample name, LW means liquefied driftwood and indicates the solvent: wood meal volume ratio after LW.



Figure 7. Comparison of residue content by mixing ratio of solvent and driftwood meal.

From this graph, it can be seen that the higher the amount of solvent used, the greater the liquefaction efficiency. The point with the lowest residue content was set at a ratio of 1:7 for the solvent and a reaction time of 180 min, resulting in an average residue content of 12.4%. In terms of solvent solubility, using a larger amount of solvent provides an advantage. Therefore, the result suggested that the optimal liquefaction conditions for driftwood to produce polyurethane foam are a mixed solvent volume ratio of 1:7 and a reaction time of 180 min.

#### 3.3. Evaluation of PUFs

## 3.3.1. Functional Groups of PUF

The Fourier transform infrared spectroscopy (FT-IR; Jasco Co., Ltd., Tokyo, Japan) spectra of PUF derived from PEG and liquefied driftwood were compared [31] and shown in Figure 8. As a sample name, PUF-PEG400 means that polyurethane foam is derived from polyethylene glycol. PUF-LW 1:7 means that the polyurethane foam is derived from liquefied driftwood.

The presence of urethane bonding and the amido II peak (1530 cm<sup>-1</sup> OCON-H) were observed in the PUF derived from driftwood. In addition, typical absorption bands on polyurethane such as CH<sub>3</sub> stretching (2970 cm<sup>-1</sup>), CH<sub>2</sub> Stretching (2870 cm<sup>-1</sup>), C=O Stretching (1720 cm<sup>-1</sup>), and C-O-C stretching (1090 cm<sup>-1</sup>) were also observed, respectively. Thus, the spectrum closely matched that of the PUF derived from polyethylene glycol (PEG) 400, leading us to conclude that the fundamental chemical structures of the two foams were the same.



**Figure 8.** FT-IR spectra comparison of Polyurethane foam derived from PEG400 (**left**) and derived from liquefied driftwood (**right**).

3.3.2. Morphology of Polyurethane Foam (PUF)

The morphology of PUF was examined using scanning electron microscopy (SEM) and is shown in Figure 9. The observation magnification is 100 times in three samples. There was a difference in the micro-porosity of the cells between the samples rather than in the cell sizes in each sample. These results indicate that the number of micro-pores in the cells increased in the following order: PUF-PEG400 < PUF-LW7:1 (non-residue) < PUF-LW7:1. The cell size of PUF-LW7:1 was around 300  $\mu$ m, and that of PUF-PEG400 was about 400  $\mu$ m. This affected the foam density and the water absorption rate described next.

PUF-LW7:1 (non-residue) PUF-LW7:1 PUF-PEG400

LW: Liquefied driftwood PEG400: Polyethylene glycol 400

Figure 9. SEM images of foams.

As a sample name, PUF-PEG400 means polyurethane foam derived from polyethylene glycol. PUF-LW 1:7 means the polyurethane foam derived from liquefied driftwood.

3.3.3. The Density and Water Adsorption of PUF

The results of the density and water adsorption of PUF are shown in Table 3. As a sample name, PUF-PEG400 means polyurethane foam derived from polyethylene glycol. PUF-LW 1:7 means the polyurethane foam derived from liquefied driftwood. Based on the scanning electron microscopy (SEM) images, variations in the number of micropores were observed, so each sample exhibited slightly different values. Conversely, the water adsorption of PUF derived from driftwood was significantly greater than that of Polyethylene glycol (PEG)400. This outcome can be attributed to the presence of micropores, as observed in the SEM images, which facilitated the retention of water within the cells.

	Density [kg⋅m <sup>-3</sup> ]	Water Absorption [%]
PUF-L(non-residue)	114.1	250.1
PUF-LW	108.2	423.8
PUF-PEG400	102.2	150.7
IW: Liquefied driftwood		

Table 3. Density and water absorption of foams.

LW: Liquefied driftwood.

In addition, in the preliminary experiment, it was observed that there was discoloration of the water in the beaker containing the PUF derived from driftwood after the immersion experiment. This observation suggests that the PUF derived from driftwood did not undergo a complete reaction with cyanate and polyol, and some free polyol remained in the foam. This may show that PUF derived from driftwood has more hydrophile characteristics to exhibit a higher water absorption rate.

# 3.3.4. Thermal Properties of PUF

The results obtained from Simultaneous Thermogravimetry and Differential Thermal Analysis (TG-DTA) are presented in Table 4 [19]. As a sample name, PUF-PEG400 means polyurethane foam derived from polyethylene glycol. PUF-LW 7:1 means the polyurethane foam derived from liquefied driftwood. This analyzer can simultaneously perform differential thermal analysis and thermogravimetric analysis with a single sample. There were notable differences in the thermal decomposition behavior between PUF derived from driftwood and those derived from petroleum-based polyols (PEG400). Specifically, the PUF derived from driftwood exhibited weight loss at lower temperatures compared to the foam derived from petroleum-based polyols (PEG400). This indicates the presence of low molecular weight components resulting from unreacted polyols, which contributed to the reduction in T5% and T10% values.

		$T_{max}$ [°C]				
	T <sub>5%</sub> [°C]	T <sub>10%</sub> [°C]	T <sub>max1</sub>	T <sub>max2</sub>	T <sub>50%</sub> [°C]	
PUF-LW 7:1	282.20	311.39	293.12	408.88	417.89	
PUF-LW7:1 (non-residue)	279.17	306.44	292.29	411.90	415.92	
PUF-PEG400	307.76	334.18	361.70	455.02	399.12	

Table 4. Characteristic degradation temperature of foams.

From this perspective, the PUF derived from petroleum-based polyols demonstrated improved initial weight loss behavior and thermal stability. Conversely, the PUF derived from driftwood exhibited a higher T50% temperature compared to the foam derived from petroleum-based polyols (PEG400). This can be attributed to the presence of driftwood components, particularly heat-resistant substances such as lignin, which remain as residues and consequently raise the temperature of weight loss.

#### 3.3.5. Biodegradability of PUF

The results of the biodegradability assessment of PUFs are presented in Figure 10. PUF derived from driftwood exhibited an average degradation rate ranging from 5.2% to 9.2% after a three-month testing period. In contrast, PUF derived from polyethylene glycol (PEG) demonstrated an average degradation rate of 2.5%. Notably, PUF derived from driftwood with residue exhibited a significant weight loss, indicating the substantial contribution of driftwood components to the biodegradation of PUF.



Figure 10. Biodegradability assessment of PUF.

In general, the decomposition of PUF can be attributed to hydrolysis, light oxidation, thermal oxidation, and ozone degradation. Furthermore, Zhang et al. (2022) concluded, through Fourier transform infrared spectroscopy (FT-IR) analysis, that PUF biodegradation occurs due to the release of lower-molecular-weight compounds from the surface, resulting from the hydrolysis of ester bonds, as well as the acid hydrolysis of urea and urethane linkages. This suggests the possibility of acid hydrolysis occurring without the need for pH adjustment during the production of PUF after the liquefaction of driftwood.

## 4. Conclusions

In this study, the collected driftwood exhibited some decay on the surface, but the results of the componential analysis revealed sufficient quantities of lignin and cellulose for utilization. Consequently, the results suggested that driftwood could have the potential to serve as a valuable biomass resource.

Using this driftwood, preparing bio polyols through the liquefaction process was carried out successfully. Optimizing this process, optimal results were achieved with the lowest residue rate, resulting in high-quality foam cells. The optimized conditions included a polyethylene glycol 400 (PEG400): Glycerol ratio of 70:30, a reaction temperature of 150  $^{\circ}$ C, a reaction time of 180 min, and a mixed solvent weight ratio of 1:7 to driftwood meal. Under these conditions, the preparation of PUF and various tests, including thermal analysis, morphology observation, water absorption, and biodegradation assessment, were carried out.

The results indicated a slight decrease in the initial thermal degradation temperature of the PUF derived from driftwood, primarily attributed to the carbonization of low molecular weight biomass components. However, the weight loss temperature at T50% increased due to this carbonization effect. Moreover, morphology observation revealed the presence of numerous micro-pores within the cell core of the PUF derived from driftwood, contributing to enhanced water adsorption to become more continuous pores. Polyurethane is a hydrophobic material, so due to the higher water absorption rate and its pore structures and sizes, polyurethane foam derived from driftwood becomes more sensitive to being affected by the environment. In terms of biodegradability in soil, PUF containing biopolyols from driftwood exhibited approximately three times faster degradation compared to petroleum-based PUF.

Based on these findings, the results suggest that PUF derived from driftwood demonstrates performance superior to petroleum-based PUF. This indicates that currently untapped biomass, such as driftwood, can be used to prepare polyurethane foams to replace petroleum-based PUF materials. Moreover, PUF derived from driftwood possessed unique characteristics such as higher water adsorption and biodegradability in soil, setting them apart from their petroleum-based counterparts.

**Author Contributions:** G.M.: data curation, visualization, investigation, writing—review and editing; A.N.: writing—original draft, data curation, conceptualization, methodology, software, visualization, investigation; W.W.: supervision, writing—review and editing; Q.W.: supervision, writing—review and editing, resources. All authors have read and agreed to the published version of the manuscript.

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