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Research article

Effect of plasticizer and carboxyl methyl cellulose (CMC) on degradable plastics from rice straw and palm fiber

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Abstract: This study used rice straw-based and palm fiber-based degradable plastics with glycerol and sorbitol. The strength of rice straw cellulose-based degradable plastics using 20% glycerol ranged from 2 to 5.75 MPa. Similarly, the strength of palm fiber cellulose-based degradable plastics using 40% sorbitol ranged from 5 to 11.13 MPa. In a chemical analysis, the peaks between 3444.87 cm^{-1} and 3651.25 cm^{-1} represented the O–H stretching of the alcohol group. This is shown by the C–O–H hydroxyl group at the wave numbers of 1627.92, 1724.36, and 1745.58 cm^{-1}. Moreover, these groups are hydrophilic, binding water, so they can be degraded by microbial activity in the soil. In the thermal analysis, degradable plastics from rice straw lost a lot of weight between 431.53 and 520.79 °C. Plastics derived from palm fibers as green products also showed extreme weight loss between 334.28 and 482.20 °C. Most of the material was decomposed at 600 °C. Both types of samples lost a lot of hydrogen groups and started to decompose and depolymerize. Rice straw plastic absorbed 10.73%–20.23%

of water, while palm fiber plastic absorbed 15.34%–85.01%. The lowest water absorption rates were observed in rice straw and palm fiber degradable plastics. Rice straw and palm fiber cellulose plastics broke down in 45–48 days, in line with the American Standard Testing and Materials (ASTM) D-20.96 standard, which says that degradable plastic should take no more than 180 days to break down.

Keywords: glycerol; sorbitol; rice straw; palm fiber; degradable plastics; green products

1. Introduction

The global consumption of plastic has been increasing exponentially, reaching 359 million tons in 2018, a significant rise from the 245 million tons consumed in 2008. Projections indicate that this figure will reach three times the current level by 2050. Despite extensive plastic production since the 1950s, no strategy has been implemented to address rising plastic use and its environmental impact [1]. The conventional PET plastic has a decomposition period of approximately 23–48 years in the environment. This presents a significant challenge to the global community, given the growing concern surrounding plastic waste [2]. The expansion of the plastics industry is a prerequisite for meeting the demands of a growing global population. However, it must also be considered that the production of conventional plastics is based on the availability of fossil fuels and the effects of the resulting waste on living organisms and the environment [3]. The presence of plastic waste in the environment has been linked to adverse effects on human health and the natural environment. This is due to the fact that plastic waste cannot be decomposed naturally. Plastic cannot simply be incinerated as it is toxic and poses health risks to living organisms and the environment. People are also debating whether recycled plastic is safe and cost-effective, as it will affect human life-cycle assessment for future sustainability.

One solution is to use natural and biodegradable plastics from agricultural waste. Cellulose can be produced to make biopolymers, as an agricultural innovation that can increase added value. Cellulose fibers, cellulose derivatives, and nanocellulose are used in composites and nanocomposites [4]. Natural fibers have low density and suitable stiffness and mechanical properties, and present disposability and regenerability. In addition, plastic materials from natural fibers are recyclable and degradable [5]. The use of cellulose in plastic bases represents an attempt to develop degradable plastics as an alternative to those currently derived from petroleum. Cellulose fibers are used to make films that are stronger and more durable [6]. Cellulose can be obtained from renewable resources and is degradable and environmentally friendly, making it an alternative to conventional plastics as packaging materials. Natural materials are popular because they are safe, biodegradable, and sustainable and can support a circular economy.

In the case of thermoplastic starch/beeswax composites using coconut fiber and glycerol, the research of Jumaidin et al. [7] showed a large increase in tensile strength and Young's modulus up to 20.7 MPa and 2890 MPa for samples with 50 wt% fiber content. The findings of a study by Demirci et al. [8] on polymer composites based on carboxymethyl cellulose cryogels make these natural synthetic polymer composites promising materials for biotechnological and biomedical applications. A previous study [9] evaluated the effect of coconut fiber and glycerol addition on water absorption and mechanical properties of corn starch bioplastics. The results showed that the bioplastic absorbed slightly more water (26.3%) after 24 h, but the addition of coconut fiber could increase the tensile strength and elongation of the bioplastic. The tensile strength obtained was 0.22 N/mm^2 and the elongation was 19.55%.

Carboxymethyl cellulose (CMC) has negatively charged hydroxyl groups and carboxylic acid ester groups. This makes it more water-dispersible during active substance delivery, which helps achieve targeted release and improves bioavailability. CMC is widely used because it is highly biocompatible, degradable, and relatively inexpensive [10]. The addition of plasticizers and CMC to cellulose-based degradable plastics aims to improve the optimal characteristics of degradable plastics, especially mechanical properties. In this research article, we will compare the characteristics of two degradable plastics, namely rice straw cellulose-based degradable plastics using glycerol and CMC and palm fiber cellulose-based degradable plastics using sorbitol and CMC. Caicedo [11] examined the effect of a sorbitol plasticizer content of 30% (w/w) on corn starch/PVOH/chitosan composites in tensile strength (21.7 ± 1.1 MPa). This study shows that corn starch/PVOH/chitosan is a good degradable packaging material and sorbitol is the best plasticizer for it. Palm fiber is a natural fiber that comes from different parts of the palm tree (*Borassus flabellifer*), which grows in large numbers in the southern parts of India. Waste from agricultural, wood, and plant materials offers great potential for diverse value addition due to its excellent physicochemical properties [12]. The chemical structure of natural or plant fibers includes cellulose, hemicellulose, lignin, pectin, and other materials [13].

There are several variations in the concentration of glycerol, sorbitol, and CMC used. The variations of glycerol and sorbitol used are 10%, 20%, 30%, and 40%. The variations of CMC used are 5%, 10%, 15%, and 20% in rice straw cellulose-based degradable plastics and 0%, 10%, 20%, and 30% in palm fiber cellulose-based degradable plastics. Rice straw is composed of several primary chemical elements, including cellulose (28%–48%), lignin (12%–16%), ash (15%–20%), and silica (9%–14%). Palm fiber, on the other hand, consists of holocellulose (59.6%), lignin (28.5%), lipids (1.9%), protein (3.6%), ash (5.6%), and other minor elements (0.8%) [14]. This research presents novelty by evaluating degradable plastics from rice straw and palm fiber cellulose using plasticizer and CMC as a filler. Previously, researchers have developed bioplastics using mineral fillers such as mica, talc, kaolin, wollastonite, calcium carbonate, silica, and montmorillonite [15,16]. A previous study found that adding a 2.0 wt% silica compound and glycerol to a sago starch/polyvinyl alcohol (PVA) film made it stronger and more flexible than a film without added silica [17]. In another study, bio-plasticizers were successfully extracted from rice straw, and their efficacy was demonstrated in chitosan polymer coatings. Polymers based on chitosan have an exceptional hardness of 300 MPa due to their dense structure and strong chitosan linkages [18]. Researchers have previously examined the properties of bioplastics containing glycerol (10%, 20%, and 30% by weight) and citric acid–epoxidized palm oil (CAEPO) using a method called solution casting. CAEPO was synthesized using CA and EPO. The type and amount of these plasticizers affected how strong and heat resistant they were, how long they took to break down, and how well they could be used in compost [19]. Nature-based plastics also have disadvantages. They do not have the same mechanical properties as conventional plastics, so technology is needed to improve them. Mechanical properties can be improved by using natural or synthetic materials. The use of plasticizers with a mixture of CMC can improve the morphological, physical, and mechanical characteristics of degradable plastics. Cellulose types and plasticizer/CMC concentrations help determine the best characteristics of degradable plastics, including mechanical, thermal, functional, water, and degradable properties.

2. Materials and methods

This research followed several stages, including the preparation of rice straw and palm fiber powder, extracting cellulose, and making and testing degradable plastics. The equipment utilized in this study included beaker glasses of 500 and 1000 mL capacity, measuring cups with the same

capacities, a mesh size of 60, a digital balance, an oven tray, a spatula, a stirrer, a thermometer, a hot plate, a hot press, and a blender and iron mold size (17 cm × 15 cm and 0.2 cm thick). Materials used include sago starch, obtained from sago plantations in Sawang, North Aceh. Rice straw and palm fiber were sourced from rice plantations and producers in Kuta Makmur, North Aceh, and were subsequently processed. The cellulose-based products used included glycerol and sorbitol (Merck Millipore, 56755, CAS: 50-70-4, Calbiochem) and carboxymethyl cellulose (CMC) (Merck Millipore, 217274, CAS: 9004-32-4, Calbiochem).

The substrate for measuring cellulose viscosity consisted of 2% H_2O at 25 °C, with a viscosity range of 800–3100 mPas, in the presence of NaOH, NaOCl, and xylene (Merck Supelco 108297, Burlington, MA, USA).

Maleic anhydride (MA, 99%) was obtained from Sigma-Aldrich (8.00408.1000), while polypropylene (PP) and benzoyl peroxide (25% H_2O content, Sigma-Aldrich 801641, CAS: 94-36-0, molar mass 242.23 g/mol) were also used. Distilled water was supplied by PT Bratachem, Surabaya, Indonesia.

2.1. Preparation of rice straw and palm fiber powder

One kilogram of rice straw and palm fiber was washed with clean water. The rice straw and palm fiber were dried for 2 × 24 h outdoors and cut into 2 cm pieces. Rice straw and palm fiber were blended to make a powder, which was sieved using a 60 mesh sieve to obtain a 1 mm thick powder.

2.2. Cellulose extraction

Pre-delignification stage: Rice straw powder and palm fiber were added to distilled water in a 1:10 ratio. The solution was heated to 100 °C for 120 minutes and stirred homogeneously. The reflux was filtered to obtain solids, which were dried in an oven at 100 °C for 120 minutes.

Delignification stage: 50 g of pre-delignified rice straw and palm fiber powder were each dissolved in 10% NaOH. The rice stray powder was heated at 160 °C for 60 minutes, while the palm fiber powder was heated at 121 °C for 60 minutes. The mixture was filtered to obtain solids. The solids were mixed with a 3.5% NaOCl solution and distilled water in a 1:1 ratio, boiled for 10 minutes, then filtered, washed, and dried in an oven for 60 minutes until dry. The final product obtained was dry alpha-cellulose powder.

2.3. Synthesis of degradable plastics

100 mL of xylene was added to 25 g of polypropylene, along with maleic anhydride (1% of the xylene volume) and benzoyl peroxide (0.1% of the maleic anhydride weight). The mixture was stirred until homogeneous at 125 °C to produce Polypropylene-grafted maleic anhydride (PP-g-MA). For the preparation of degradable plastics, 12.5 g of alpha-cellulose from rice straw and palm fiber were each mixed with varying amounts of glycerol and sorbitol plasticizers (10%, 20%, 30%, and 40%). Additionally, CMC was added in different variations: 5%, 10%, 15%, and 20% for rice stray cellulose-based plastics and 0%, 10%, 20%, and 30% for palm fiber cellulose-based degradable plastics. PP-g-MA was then added and stirred evenly. The mixture was molded using a hot press at 165 °C for 8 minutes.

2.4. Characterization and analysis

The mechanical properties of rice straw cellulose-based degradable plastics were analyzed using glycerol plasticizer (20%) and CMC (10%, 20%, 30%, and 40%). Palm fiber cellulose-based degradable plastics were analyzed using sorbitol plasticizer (40%) and CMC (0%, 10%, 20%, and 30%). The mechanical characteristics, including tensile strength, elongation, and Young's modulus, were tested using a universal testing machine. The tensile strength test followed the ASTM D-638 standard, using dumbbell-shaped specimens with a 50 mm gauge length. Tensile strength and elongation were analyzed using a universal testing machine on 165 mm cut specimens and calculated using Eqs 1 and 2.

$$\sigma = \frac{F_{maks}}{A} \tag{1}$$

where σ is tensile strength (MPa), Fmax is maximum stress (N), and A is the cross-sectional area of the film (mm^2).

$$\varepsilon = \frac{\triangle l}{l_0} \tag{2}$$

where ε is the strain (MPa), l is the gauge length, l_0 is the gauge length of the pre-sample, and l is the gauge length of the test sample after elongation.

Fourier transform infrared spectroscopy (FTIR) and thermogravimetric (TGA) analysis were conducted on samples with 40% glycerol and sorbitol and 20% CMC. FTIR is a technique employed to discern the chemical bonds present in diverse materials. It entails irradiating a test sample with infrared radiation and subsequently analyzing the sample's chemical characteristics. The wavelength absorbed by the sample shows its molecular structure. This study used FTIR analysis at wave numbers 550–4000 cm^{-1}. Thermal degradation assesses the breakup of polymers caused by heat, which involves a loss of hydrogen atoms from the polymer chain. The upper temperature limit for the polymer is set by thermal degradation. TGA was used to test the thermal stability of degradable plastics.

The water resistance of cellulose-based degradable plastics was tested using the ASTM D2765 swelling analysis. Rice straw-based plastics were tested with glycerol (10%, 20%, 30%, and 40%) and CMC (5%, 10%, 15%, and 20%). The palm fiber-based plastics were tested with sorbitol (10%, 20%, 30%, and 40%) and CMC (0%, 10%, 20%, 30%). Samples were weighed before and after being soaked in a solvent for 24 hours. The swelling degree was calculated using Eq 3:

$$\text{Swelling} = \frac{\text{Weight of expanded sample} - \text{Weight of pre sample}}{\text{Pre-weight sample}} \times 100\ \% \tag{3}$$

The biodegradability of cellulose-based degradable plastics was evaluated through a burial test following ASTM G-21-70 standard. Rice straw and palm fiber-based plastics were tested with glycerol and CMC and sorbitol and CMC as above. Samples measuring 2 × 2 cm were weighed before being buried in the soil. After 3 days, samples were removed and re-weighed. Biodegradability was calculated using Eq 4.

$$\text{Biodegradabillity (\%)} = \frac{M0 - M1}{M0} \times 100\% \tag{4}$$

where M_0 is the initial mass (g), and M_1 is the final mass.

3. Results

3.1. Mechanical properties

The results regarding the mechanical properties of rice straw cellulose-based (with glycerol plasticizer at 20% and CMC at 10%, 20%, 30%, and 40%) and palm fiber cellulose-based degradable plastics (with sorbitol plasticizer at 40% and CMC at 0%, 10%, 20%, and 30%) are provided in Figure 1.

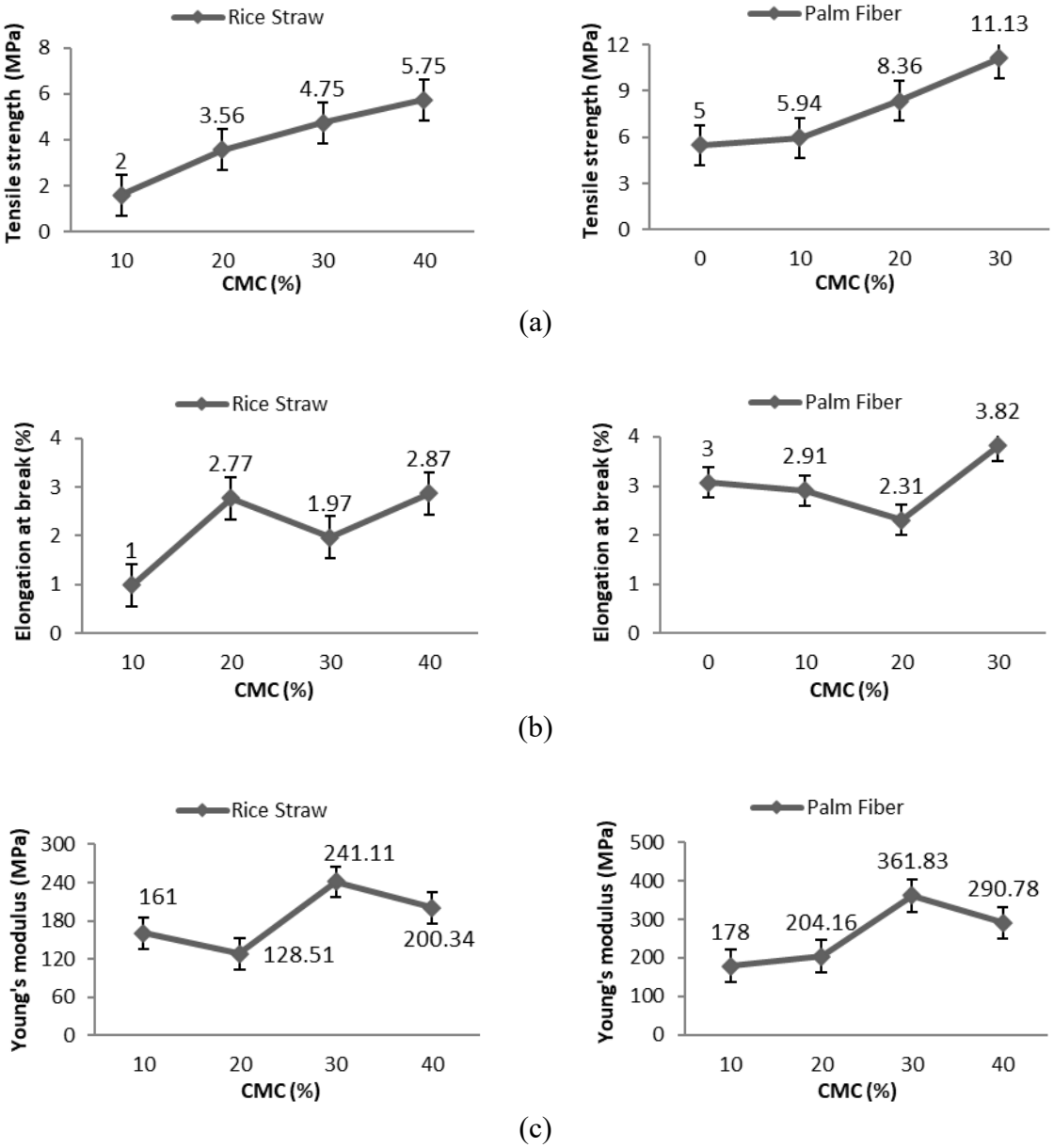


Figure 1. Rice straw and palm fiber cellulose-based degradable plastics: (a) Tensile strength (MPa), (b) elongation at break (%), (c) Young's modulus (MPa).

3.2. Chemical characterization

Fourier transform infrared spectroscopy results for rice straw cellulose-based (with glycerol at

40% and CMC at 20%) and palm fiber cellulose-based degradable plastics (with sorbitol at 40% and CMC at 20%) are shown in Figure 2(a),(b).

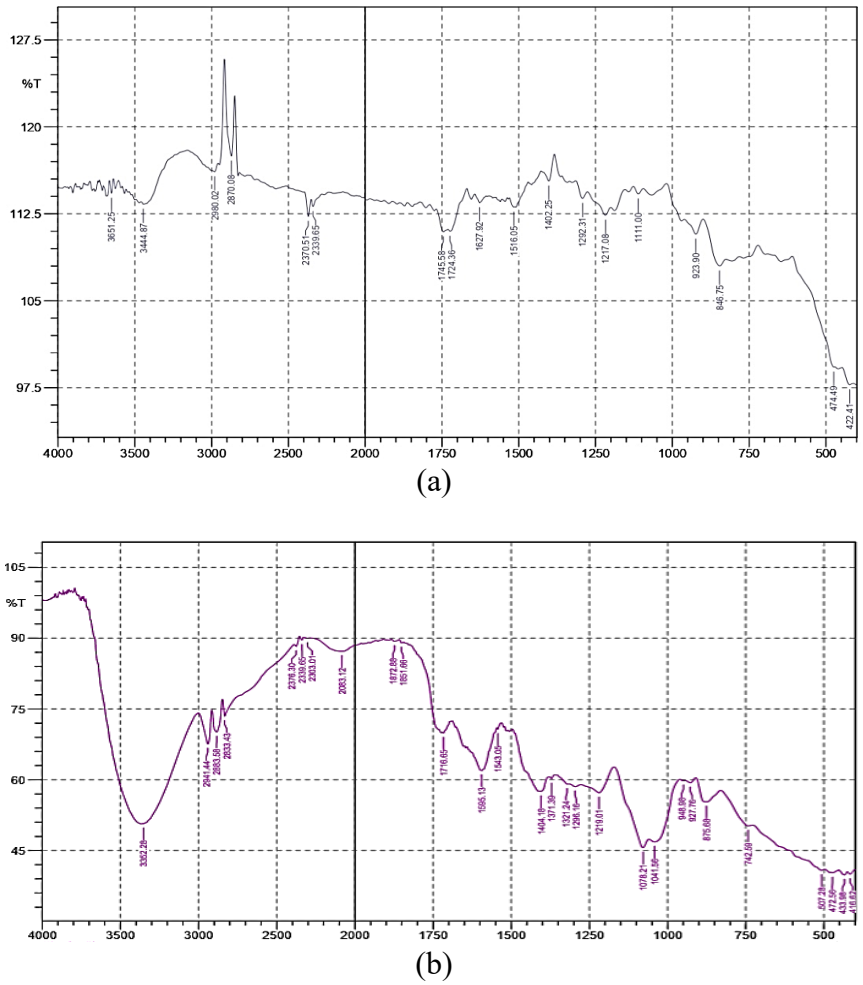
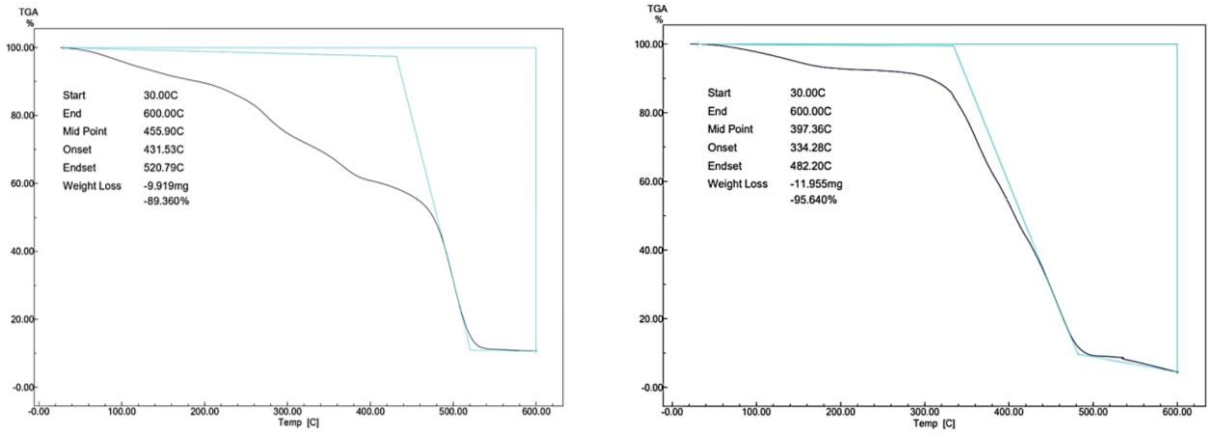


Figure 2. FTIR results for (a) rice straw cellulose-based and (b) palm fiber cellulose-based degradable plastics.

3.3. Thermal properties

The TGA test results for rice straw cellulose-based (with glycerol at 20% and CMC at 20%) and palm fiber cellulose-based degradable plastics (with sorbitol at 40% and CMC at 30%) are shown in Figure 3(a),(b).

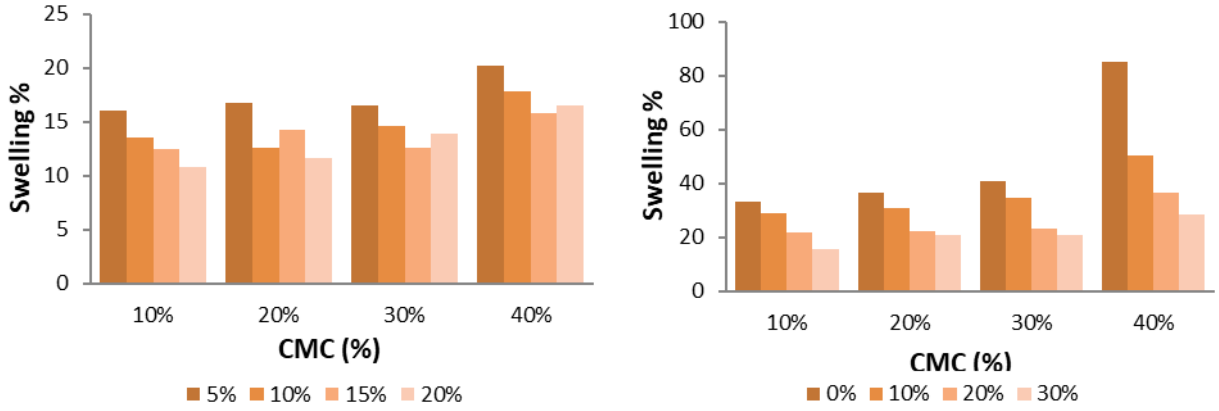


(a) (b)

Figure 3. TGA results for (a) rice straw cellulose-based and (b) palm fiber cellulose-based degradable plastics.

3.4. Water absorption

Water resistance test results for rice straw cellulose-based (with glycerol at 10%, 20%, 30%, and 40% and CMC at 5%, 10%, 15%, and 20%) and palm fiber cellulose-based degradable plastics (with sorbitol at 10%, 20%, 30%, and 40% and CMC at 0%, 10%, 20%, and 30%) are shown in Figure 4(a),(b).

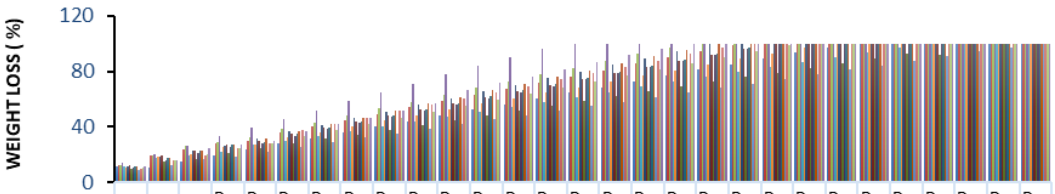


(a) (b)

Figure 4. Water absorption capacity of (a) rice straw cellulose-based and (b) palm fiber cellulose-based degradable plastics.

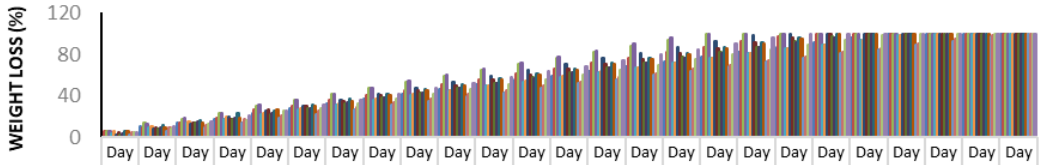
3.5. Biodegradability rate

Biodegradability rate test results for rice straw cellulose-based (with glycerol at 10%, 20%, 30%, and 40% and CMC at 5%, 10%, 15%, and 20%) and palm fiber cellulose-based degradable plastics (with sorbitol at 10%, 20%, 30%, and 40% and CMC at 0%, 10%, 20%, and 30%) are shown in Figure 5(a),(b).



	Day 3	Day 6	Day 9	Day 12	Day 15	Day 18	Day 21	Day 24	Day 27	Day 30	Day 33	Day 36	Day 39	Day 42	Day 45	Day 48	Day 51	Day 54	Day 57	Day 60	Day 63	Day 66	Day 69	Day 72	Day 75	Day 78	Day 81	Day 84	Day 87
Gliserol 10% : CMC 5%	12	11	15	19	24	28	32	36	40	44	48	52	57	61	65	69	73	77	81	85	89	93	97	100	100	100	100	100	100
Gliserol 10% : CMC 10%	12	19	24	28	30	36	41	45	50	54	59	63	67	72	76	81	85	90	94	99	100	100	100	100	100	100	100	100	100
Gliserol 10% : CMC 15%	13	19	26	29	33	39	43	48	53	58	63	68	73	78	83	88	93	97	100	100	100	100	100	100	100	100	100	100	100
Gliserol 10% : CMC 20%	14	20	27	34	39	46	52	58	65	71	78	84	90	97	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Gliserol 20% : CMC 5%	12	18	20	22	27	30	34	37	41	44	48	51	55	58	62	65	69	72	76	79	83	86	90	93	97	100	100	100	100
Glycerol 20% : CMC 10%	11	18	20	26	27	32	36	40	44	49	53	57	61	65	69	73	77	81	85	89	93	97	100	100	100	100	100	100	100
Glycerol 20% : CMC 15%	11	19	23	27	31	37	41	46	51	56	61	65	70	75	80	85	89	94	100	100	100	100	100	100	100	100	100	100	100
Glycerol 20% : CMC 20%	12	19	23	27	30	35	40	44	49	53	57	62	66	70	75	79	83	88	92	96	100	100	100	100	100	100	100	100	100
Glycerol 30% : CMC 5%	10	15	17	21	24	28	31	35	38	42	45	48	52	55	59	62	66	69	72	76	79	83	86	89	93	92	100	100	100
Glycerol 30% : CMC 10%	11	16	21	26	29	34	38	43	47	52	56	61	65	70	74	79	83	87	92	96	100	100	100	100	100	100	100	100	100
Glycerol 30% : CMC 15%	12	18	23	27	29	35	40	44	48	53	57	62	66	71	75	80	84	89	93	97	100	100	100	100	100	100	100	100	100
Glycerol 30% : CMC 20%	12	18	23	28	32	37	42	47	52	57	61	66	71	76	81	86	91	96	100	100	100	100	100	100	100	100	100	100	100
Glycerol 40% : CMC 5%	9.4	12	16	19	22	26	29	32	35	39	42	45	49	52	55	58	62	65	68	71	75	78	81	84	88	91	94	97	100
Glycerol 40% : CMC 10%	9.6	16	19	25	28	38	42	47	51	56	60	65	70	74	79	83	88	92	97	100	100	100	100	100	100	100	100	100	100
Glycerol 40% : CMC 15%	11	16	21	25	28	33	38	42	46	51	55	59	64	68	73	77	81	86	90	95	99	100	100	100	100	100	100	100	100
Glycerol 40% : CMC 20%	11	16	25	28	30	37	42	47	52	57	67	72	77	82	87	92	96	100	100	100	100	100	100	100	100	100	100	100	100

(a)



	Day 3	Day 6	Day 9	Day 12	Day 15	Day 18	Day 21	Day 24	Day 27	Day 30	Day 33	Day 36	Day 39	Day 42	Day 45	Day 48	Day 51	Day 54	Day 57	Day 60	Day 63	Day 66	Day 69	Day 72	Day 75
Sorbitol 10% : CMC 0%	4.3	10.7	14.1	17.9	23.6	27.9	32.5	37	41.6	46.2	50.8	55.4	60	64.6	69.1	73.7	78.3	82.9	87.5	92.1	96.6	100	100	100	100
Sorbitol 10% : CMC 10%	5.92	9.34	14.1	19.5	26.7	30.6	35.8	40.9	46.1	51.3	56.4	61.6	66.8	71.9	77.1	82.3	87.4	92.6	97.8	100	100	100	100	100	100
Sorbitol 10% : CMC 20%	6.37	14.7	18.4	23.9	30.9	36.3	42.2	48	53.8	59.6	65.5	71.3	77.1	82.9	88.8	94.6	100	100	100	100	100	100	100	100	100
Sorbitol 10% : CMC 30%	6.32	13.5	18.6	23.3	31.2	36.5	42.4	48.4	54.4	60.3	66.3	72.2	78.2	84.2	90.1	96.1	100	100	100	100	100	100	100	100	100
Sorbitol 20% : CMC 0%	4.4	9.57	14.6	18.3	22.4	27.3	31.8	36.2	40.7	45.2	49.7	54.1	58.6	63.1	67.6	72	76.5	81	85.5	90	94.4	98.9	100	100	100
Sorbitol 20% : CMC 10%	6.36	11.1	15.1	19.8	24	28.4	32.8	37.2	41.6	46	50.4	54.8	59.2	63.6	68	72.4	76.8	81.1	85.5	89.9	94.3	98.7	100	100	100
Sorbitol 20% : CMC 20%	3.3	8.09	13.1	19.9	25.7	31	36.6	42.3	47.9	53.6	59.2	64.9	70.6	76.2	81.9	87.5	93.2	98.8	100	100	100	100	100	100	100
Sorbitol 20% : CMC 30%	5.31	10.3	14.3	18.1	26.8	30.2	35.2	40.4	45.5	50.5	55.6	60.7	65.8	70.9	76	81	86.1	91.2	96.3	100	100	100	100	100	100
Sorbitol 30% : CMC 0%	2.99	9.01	14.9	18.4	22.9	28.4	33.3	38.2	43.2	48.1	53	57.9	62.8	67.7	72.7	77.6	82.5	87.4	92.3	97.3	100	100	100	100	100
Sorbitol 30% : CMC 10%	3.94	9.73	15.2	19.1	23.3	28.7	33.5	38.4	43.2	48	52.8	57.6	62.5	67.3	72.1	76.9	81.7	86.6	91.4	96.2	100	100	100	100	100
Sorbitol 30% : CMC 20%	6.61	11.8	16.8	24	25.5	31.9	36.9	41.9	46.9	51.9	56.9	61.9	66.9	71.9	76.9	81.9	86.9	91.9	96.9	100	100	100	100	100	100
Sorbitol 30% : CMC 30%	6.26	9.62	14.5	19.1	26.7	30.3	35.3	40.4	45.4	50.5	55.5	60.5	65.5	70.6	75.6	80.6	85.6	90.7	95.7	100	100	100	100	100	100
Sorbitol 40% : CMC 0%	2.68	6.66	9.66	14.7	19.4	23	27.2	31.3	35.5	39.6	43.7	47.9	52	56.2	60.3	64.4	68.6	72.7	76.9	81	85.2	89.3	93.4	97.6	100
Sorbitol 40% : CMC 10%	5.21	10.2	12.3	17.8	21.7	25.6	29.7	33.7	37.8	41.8	45.9	49.9	54	58.1	62.1	66.2	70.2	74.3	78.4	82.4	86.5	90.5	94.6	98.7	100
Sorbitol 40% : CMC 20%	5.59	9.14	13.7	16.3	25.5	28.1	32.8	37.5	42.2	46.9	51.5	56.2	60.9	65.6	70.3	75	79.7	84.4	89.1	93.7	98.4	100	100	100	100
Sorbitol 40% : CMC 30%	4.59	10.4	15.1	21	26.1	31.5	36.9	42.2	47.6	52.9	58.3	63.7	69	74.4	79.7	85.1	90.5	95.8	100	100	100	100	100	100	100

(b)

Figure 5. Biodegradability rate of (a) rice straw cellulose-based and (b) palm fiber cellulose-based degradable plastics.

4. Discussion

4.1. Mechanical properties

The mechanical properties of degradable plastics were evaluated to ascertain the tensile strength, elongation, and modulus of elasticity values. Figure 1(a) illustrates the tensile strength values of rice straw cellulose-based degradable plastics utilizing 20% glycerol, which ranged from 2 to 5.75 MPa. Similarly, the tensile strength values of palm fiber cellulose-based degradable plastics using 40% sorbitol ranged from 5 to 11.13 MPa. The highest tensile strength values were found in rice straw cellulose-based degradable plastics using 40% CMC and in palm fiber cellulose-based degradable plastics using 30% CMC. The CMC used affects the mechanical properties of the plastic. Bioplastics made with high levels of amylose (75%) and 20% glycerol seem to be more flexible and less strong due to the higher concentration of propylene oxide (6%–12%, w/w starch) present. The tensile strength was found to be 18.90 MPa (native starch), 15.66 MPa (6% propylene oxide), and 8.85 MPa (12% propylene oxide) [20]. A comparison of the tensile strength values obtained in this study with those reported for HDPE (11.0–25.0 MPa) and PP (15.0–45.0 MPa) based on the Mat Web Material Property database for the category "Polypropylene, Extrusion Grade" reveals that the former is not comparable. It can be postulated that the stirring factor exerts an influence on the synthesis of degradable plastics, which in turn affects the tensile strength of the resulting material.

Elongation is a measure of a material's capacity to undergo tensile deformation when subjected to a tensile force. It is a fundamental property that determines the elastic behavior of a material. In the context of degradable plastics, a higher elongation value indicates greater elasticity, allowing the material to undergo a greater degree of deformation before reaching its breaking point. From Figure 1(b), it can be seen that the highest elongation test value of rice straw cellulose-based degradable plastic (2.87%) is with 40% CMC while in palm fiber cellulose (3.82%) is with 30% CMC. The impact of CMC incorporation on the properties of chitosan-based bioplastic was investigated by Putranti and Nugraheni [21]. The addition of 0.5% CMC, 2% chitosan, and 0.5% glycerol resulted in a tensile strength of 12.83 MPa and an elongation of 41.76%. The Indonesian National Standard (SNI) 7188.7:2016 sets the percentage elongation of bioplastic at 21%–220%. The mean value of percentage elongation for bioplastics produced across all treatments did not reach the required standard for SNI compliance. According to the Mat Web Material Property database within the Polypropylene, Extrusion Grade category, the observed elongation value falls within a range comparable to that observed in HDPE (200%–500%), although it is not comparable to the elongation value observed in PP (530%–700%).

The tensile strength and elongation values increase with increased addition of CMC. However, at 30% CMC, the elongation value decreases. This may be affected by the incomplete stirring factor. The elasticity of a material is related to its ability to stretch. The elastic modulus is a measure of how elastic the material is and how well it can resist stress. If the force stops, the object will return to its original state. The ratio of stress and strain is constant, and the modulus of elasticity is the magnitude of this constant. The greater the modulus of elasticity, the stiffer and less deformable the material. In Figure 1(c), the elastic modulus value of rice straw cellulose-based degradable plastics using 20% glycerol ranged from 128.51 to 241.11 MPa, while that for palm fiber cellulose-based degradable plastics with 40% sorbitol ranged from 178.36 to 361.83 MPa. CMC films with a concentration of 30% showed an elastic modulus 15 times higher than other concentrations. Although the CMC film showed a greater modulus of elasticity, the addition of up to 40 wt% CMC in the cellulose film did not cause a significant difference in the stiffness of the material [22]. The modulus elasticity obtained is not comparable to the modulus elasticity of Polyethylene Bralen RA 2-63 foils (222.73–298.24 MPa) [23].

4.2. Chemical properties analysis

The samples' cellulose and plasticizer sources (i.e., CMC, glycerol, and sorbitol) were grouped based on their combined nature. In Figure 2(a) of rice straw cellulose-based degradable plastics plasticized using glycerol, the typical peaks between 3444.87 and 3651.25 cm^{-1} represent the O–H stretching of the alcohol group. Similar peaks have also been observed in palm coir cellulose-based degradable plastic samples plasticized using sorbitol, with peaks at approximately 3352.68 cm^{-1} representing the O–H stretching of the alcohol group. In degradable plastic from palm fiber with sorbitol, the wave numbers 3352.28, 2941.44, 2883.58, and 2833.43 cm^{-1} were present, which are OH groups. Razali et al. [24] studied the pulping of cellulose fibers from rice straw as a polymer base material and observed typical bands at wave numbers 3327 cm^{-1}, such as OH stretching. Łopusiewicz et al. [25] looked at composite films made from CMC with fungal melanin and carvacrol. They found that the hydroxyl group of cellulose showed up at 3200–3350 cm^{-1}. The peaks in Figure 2(a) show that the rice straw cellulose-based degradable plastics contains glycerol, which has a C–O–H hydroxyl group at the wave numbers 1627.92, 1724.36, and 1745.58 cm^{-1}; Figure 2(b) shows that palm fiber cellulose-based degradable plastics containing sorbitol have peaks of wave numbers 1695.13 and 1716.65 cm^{-1}. This is similar to the work by Navasingh et al. [26] on starch-based bioplastics with glycerol plasticizer mixing, finding wave numbers 1624 and 1759 cm^{-1}, which is a C–O–H group. The cluster content identified in the FTIR analysis of rice straw and palm fiber cellulose-based degradable polymers is an organic group, indicating that the plastic is hydrophilic and binds to water. This results in its easy degradation in soil. Furthermore, this suggests that the degradable plastic possesses a greater number of free hydroxyl groups (–OH) due to the reduction in atoms that can bond with hydrogen. The –OH groups are derived from sodium hydroxide (NaOH) or from other extractives.

4.3. Thermal properties analysis

The resulting curve in the TGA analysis is a plot of the change in mass versus temperature. This curve is presented in Figure 3 and represents the TGA curve. The TGA curve is a plot of the decrease in mass (in percentage) on the y-axis and the temperature increase on the x-axis. Figure 3 shows that the temperature of each polymer variation increases due to CMC, plasticizers, and cellulose fibers in the materials used in degradable plastics. Figures 3(a),(b) show a decrease in mass at 30 °C. At these temperatures, the plastic loses weight because of contaminants and other additives. Figure 3(a) shows that extreme weight loss starts between 431.53 and 520.79 °C. At 600 °C, most of the material is decomposed. Figure 3(b) shows that the weight loss of palm fiber degradable plastic with sorbitol is more extreme, with a range between 334.28 and 482.20 °C. At 600 °C, most of the material is decomposed. Both samples of degradable plastic underwent significant thermal degradation, which involved the loss of hydrogen groups, decomposition, and depolymerization [27].

Prisacariu et al. [28] observed that too much cellulose can stop polymers from breaking down. The two samples had slightly different weight losses. The plastic with rice straw cellulose was 89.36% degraded with 9.91 mg remaining, and the degradable plastic with palm fiber cellulose was 95.64% with 11.95 mg remaining. The large weight loss at 250–300 °C is due to gelatin and starch decomposition. The sample can be used at high temperatures [29]. Terán et al. [30] evaluated how the addition of eucalyptus, tea tree (TT), rosemary, and chiriyuyo to potato starch, glycerin, and water affects the structure and properties of thermoplastic starch. The TGA analysis demonstrated that samples exhibited a shift toward lower temperatures with an increase in TT. This was observed at concentrations of 0.5, 1.2, and 7 g/100 g TPS, corresponding to temperatures of 304.6, 301.6, 300.6,

and 294.2 °C. Authors observed that higher amounts of tea trees in thermoplastic starch result in intensive changes to TPS crystals. The changes in the TGA thermogram are due to heat and the way degradable plastics vary. It can be demonstrated that an increase in residual weight will result in an improvement in thermal resistance. In this study, degradable plastics based on rice straw cellulose and palm fiber using plasticizers and CMC showed good thermal stability.

4.4. Water absorption analysis

Water absorption evaluates the plastic's resistance to water. This study used glycerol and sorbitol (at 10%, 20%, 30%, and 40%) in rice straw cellulose with CMC (5%, 10%, 15%, and 20%) and palm fiber cellulose with CMC (0%, 10%, 20%, and 30%) to evaluate water resistance of degradable plastic. As illustrated in Figures 4(a),(b), the incorporation of varying concentrations of CMC, plasticizers, and cellulose types has been observed to enhance the water resistance of degradable plastics. Degradable plastics using rice straw cellulose have a smaller water absorption value (10.73%–20.23%) than palm fiber cellulose (15.34%–85.01%). The use of 10% glycerol and 20% CMC in rice straw cellulose-based degradable plastics and 10% sorbitol and 30% CMC in palm fiber cellulose-based degradable plastics leads to low water absorption (10%–15%). Babalola et al. [31] studied the water absorption values (27.3–42.9%) of coconut coir fiber-based bioplastics with the addition of glycerin (5%, 10%, 15%, 20%). If water soaking is limited, mold cannot grow on the surface of degradable plastics. Cellulose fibers soak up a lot of water, which can break down the mechanical performance of their composites. Cellulose fibers can absorb moisture due to the strong hydrogen bonds between cell wall macromolecules. When a fiber touches water, the hydrogen bond breaks and a new hydrogen bond is formed between the –OH group and the water molecule. The –OH group is the main source of water absorption in cellulose fibers. Removal of these groups can have a positive effect on the water absorption of cellulose fibers. Cellulose fibers can now be made to absorb less water by modifying their surface and coating them in a polymer [32].

Cellulose, hemicellulose, and lignin, which make up cellulose fibers, have hydroxyl groups that bond to water molecules. The chemical composition of cellulose fibers has an effect on their water absorption capacity. Cellulose with different fibers shows different water absorption capacities due to variations in chemical composition. The water absorption capacity depends on many factors, including cellulose fibers, their properties, type, permeability, temperature, media pH, humidity, fiber strength, water exposure, polymer viscosity, cross-linking, crystallinity, polarity, diffusivity, and surface bonding [33,34]. Tessanan et al. [35] studied how the water resistance of degradable plastics made from pineapple stem starch and PLA changed over time. They found that water absorption capacity increased with longer immersion times but eventually stopped after a certain period. A previous study [36] created yam starch-based polymers using polypropylene and cassava starch. The PP-g-MA polymer was more water resistant than the blend without PP-g-MA. Blends without PP-g-MA absorbed more water than those with PP-g-MA. Shrestha et al. [37] made starch-based bioplastics with glycerol and polyvinyl alcohol (PVA) and tested them for water resistance, biodegradability, and acid-base resistance. More starch in the blend resulted in more water absorption. The bioplastic with more starch in it broke down more quickly than the others. The bioplastics with more starch were resistant to acids and bases for 45 and 42 hours, respectively. Putri et al. [38] studied the effect of CMC on edible film from sorghum starch and stated that the addition of CMC reduces the percentage of water absorption in the film. The decrease in water absorption rate by degradable plastic blends with increasing CMC concentration is in line with the results of the study.

Glycerol and sorbitol are now used very widely. These compounds are stable and non-toxic, which makes them a good choice for further research. Plasticizers can also be added to polymers to make them more flexible and improve their water vapor permeability. CMC can bind and absorb water because it has a hydroxyl group, which allows it to be biodegradable. CMC is needed to control the water content and improve texture and stability. CMC can increase viscosity and tensile strength but decreases elongation percentage [39].

4.5. Biodegradability rate analysis

Soil bacteria and fungi break down plastic after burial. Figures 5(a),(b) show that rice straw and palm fiber cellulose-based degradable plastics using plasticizers and CMC decomposed completely within 45–84 days in the soil. The addition of plasticizers and the mixing of materials with CMC have an effect on the degradation of degradable plastics. The use of 10% glycerol and 20% CMC in rice straw cellulose degradable plastics resulted in a faster decomposition at 45 days; the use of sorbitol at 10% and CMC at 20% and 30% on palm fiber plastic resulted in faster decomposition at 51 days. Glycerol plasticizer has hydrophilic properties; hence, the water absorption rate is higher and can provide a conducive space for developing microorganisms. Lignin in cellulose fibers can hinder them from breaking down. The removal of lignin can be achieved through the use of various lignin-degrading compounds, such as sodium hydroxide (NaOH). This compound has been demonstrated to exert a pronounced effect on the delignification process, thereby facilitating the removal of lignin [40]. Subramanian's research in 2021 [41] showed that using more NaOH made sago starch plastics break down faster. Sago starch bioplastics lost 79% and 74% of their weight after three days. Sago starch contains amylase resistance.

The ASTM D-6002 standard, entitled "Guide for Assessing the Compostability of Environmentally Degradable Plastics" and the ASTM D-20.96 standard on environmentally degradable plastics set forth the requisite criteria for the compostability of plastic materials. These standards stipulate that products comprising a single polymer, whether a homopolymer or a random copolymer, must undergo a conversion process whereby 60% of the organic carbon present in the material is transformed into carbon dioxide by the conclusion of the specified test period, which may extend up to 180 days. Hence, the duration of decomposition of rice straw and palm fiber cellulose-based plastics met this standard [42]. The degradation rate of degradable plastics depends on the material, soil moisture, and environment [43]. In a recent study, Elgharbawy et al. [44] demonstrated that the addition of starch, cellulose, or cellulose derivatives to PVA results in enhanced solubility and biodegradability of the plastic in soil.

5. Conclusions

The tensile strength values of rice straw cellulose-based degradable plastics utilizing 20% glycerol ranged from 1.59 to 5.75 MPa, while that of palm fiber cellulose-based degradable plastic using 40% sorbitol ranged from 5.47 to 11.13 MPa. The highest elongation value of rice straw cellulose-based degradable plastics was found with 40% CMC, with an elongation value of 2.87%, while that of palm fiber cellulose was found with 30% CMC, with an elongation value of 3.82%. The elastic modulus value of rice straw cellulose-based degradable plastics using 20% glycerol ranged from 128.51 to 241.11 MPa, while that of palm fiber cellulose-based degradable plastics with 40% sorbitol ranged from 178.36 to 361.83 MPa. The cluster content of degradable plastics, as determined by FTIR analysis, is composed of organic groups. This renders the plastic hydrophilic, which facilitates

its binding to water, thereby facilitating its degradation in the soil. The TGA analysis shows that the degradable plastics present good thermal stability. The use of 10% glycerol and 20% CMC in rice straw cellulose-based degradable plastics and 10% sorbitol and 20% CMC in palm fiber cellulose-based degradable plastics leads to a small water absorption of 10%–15%. Cellulose-based degradable plastics in this study degraded completely at ± 45 days.

These degradable plastics were produced using natural base materials obtained from rice straw and oil palm waste. Cellulosic fiber production is a by-product of this waste, with the potential to improve the economic growth of rice and palm oil farmers and traders since the utilization of these wastes has not been optimal to date. This biodegradable plastic product is expected to be able to replace commercial and conventional plastics, with an impact on environmental and human health, aiding sustainable growth and supporting economic development as has been done by several developing countries.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare no conflict of interest.

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