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Synthesis of Biodegradable Bioplastic from Xanthan Gum (XCD) Recovered from Hi-Vis Sweep Waste Generated during Well Service Operations in Bunyu Field

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Abstract

Well service operations in the oil and gas industry utilize sweep fluids based on xanthan gum (XCD), which generate high-viscosity waste with the potential to cause environmental pollution. Due to its natural polymer characteristics, XCD waste has significant potential to be utilized as a raw material for biodegradable bioplastic production. This study aims to synthesize and characterize biodegradable bioplastics derived from XCD waste generated from Hi-Vis sweep operations during well service activities in Bunyu Field. The bioplastics were prepared using the solution casting method with variations in XCD concentration (1.0–2.0%), plasticizer type (glycerol and sorbitol), and plasticizer concentration (20–40%). The resulting bioplastics were characterized through film thickness, water absorption, and biodegradation rate tests. The experimental data were further analyzed using Response Surface Methodology (RSM) based on a Central Composite Design (CCD).The results showed that increasing plasticizer concentration enhanced both water absorption capacity and film flexibility. Bioplastics plasticized with glycerol exhibited a higher biodegradation rate compared to those containing sorbitol. These findings demonstrate that XCD waste from Hi-Vis sweep operations can be effectively valorized as an environmentally friendly raw material for biodegradable bioplastic production.

Keywords : Xanthan Gum, Sweep Hi-Vis, Plasticizer, Biodegradation

INTRODUCTION

The oil and gas industry is one of the strategic sectors that plays an important role in providing national energy supplies (Maharani & Akbar, 2023). In well service activities, various types of fluids are used to support the success of well operations. One of the commonly used fluids is Xanthan Gum (XCD)-based High Viscosity Sweep (Hi-Vis), particularly in wells with depths exceeding 1,500 mMD (Akpan et al., 2020). This fluid functions to lift cuttings, drill-out cement debris, and residual drilling mud, thereby maintaining clean perforation intervals and ensuring effective operations (Katende et al., 2020; Al-Rubaii et al., 2023). Xanthan Gum (XCD) is a natural biopolymer produced through the fermentation of Xanthomonas campestris, which has the ability to generate high viscosity at low concentrations (García-Ochoa et al., 2000). These characteristics make XCD widely used in the petroleum industry because it can improve particle suspension capacity and maintain fluid stability during well operations. In addition, the use of polymer-based fluids has been proven to enhance operational efficiency while reducing the risk of formation damage that may decrease reservoir productivity (Echt et al., 2020; Liu et al., 2020). Despite providing significant operational benefits, the extensive use of XCD generates high-viscosity waste that may cause environmental pollution if not properly managed. Hi-Vis sweep waste is generally difficult to

degrade naturally and may affect soil and water quality around operational areas. This condition encourages the development of more sustainable and value-added waste management technologies.

On the other hand, XCD possesses biodegradable, non-toxic, and film-forming properties, making it a potential raw material for biodegradable bioplastics. Several studies have shown that xanthan gum can be combined with starch, chitosan, and plasticizers such as glycerol to produce bioplastic films with good mechanical properties and biodegradability (Patel et al., 2020; Sapper et al., 2019; Yermagambetova et al., 2024). The utilization of biopolymers as raw materials for bioplastics has become increasingly important due to the growing demand for environmentally friendly materials capable of replacing petroleum-based plastics (Emadian et al., 2017). However, most previous studies have utilized pure xanthan gum, while the utilization of XCD-based Hi-Vis sweep waste directly generated from well service activities in oil and gas fields remains very limited. Therefore, this study was conducted to investigate the utilization of XCD waste as a raw material for biodegradable bioplastics and to optimize its formulation using the Response Surface Methodology (RSM). This approach is expected to provide an alternative waste management strategy that supports circular economy principles while generating value-added products for the oil and gas industry (Geissdoerfer et al., 2017).

XCD possesses characteristics that support its utilization as a raw material for biodegradable bioplastics. Its polysaccharide structure, containing numerous hydroxyl groups, enables the formation of film networks through hydrogen bonding, allowing it to function as the primary matrix in bioplastic production (Patel et al., 2020). However, films based on pure xanthan gum are generally rigid and brittle, thus requiring the addition of plasticizers and fillers to improve their mechanical properties (Dhalsamant, 2025). In this study, glycerol was used as a plasticizer to enhance film flexibility, while tapioca was selected as a filler due to its high starch content, biodegradable nature, wide availability, and ability to improve the compactness and strength of the bioplastic structure through interactions with the XCD matrix (Müller et al., 2009; Sanyang et al., 2016). The combination of these three components is expected to produce bioplastics with mechanical properties and biodegradability suitable for environmentally friendly applications.

METHOD

Materials

The primary material used in this study was xanthan gum waste (XCD) obtained from High-Viscosity Sweep (Hi-Vis Sweep) operations conducted during well service activities at Bunyu Field, North Kalimantan, Indonesia. Xanthan gum is an anionic polysaccharide widely utilized as a viscosifying agent in drilling fluids and well intervention operations due to its high viscosity, shear-thinning behavior, stability under various salinity, temperature, and pH conditions, as well as its biodegradable nature (García-Ochoa et al., 2000; Patel et al., 2020). Additional materials included glycerol and sorbitol as plasticizers, tapioca starch as filler, distilled water as solvent, and soil as a biodegradation medium. Glycerol and sorbitol were selected because of their ability to enhance polymer chain mobility and improve film flexibility, while tapioca starch was employed as a reinforcing filler due to its high starch content, biodegradability, availability, and compatibility with xanthan gum matrices (Müller et al., 2009; Oliveira et al., 2025; Sanyang et al., 2016).

Preparation of Xanthan Gum Waste

Xanthan gum (XCD) waste obtained from High-Viscosity Sweep (Hi-Vis Sweep) operations was first processed through a solid–liquid separation stage to remove impurities carried during well service activities, such as sand, drilling cuttings, and other solid residues. The sample was allowed to stand for 24 hours to facilitate gravitational sedimentation, enabling particles with higher density to settle at the bottom of the container. The supernatant containing xanthan gum was then separated from the sediment and subsequently filtered using filter paper to remove any remaining fine solid particles. The filtered XCD solution was then used as the raw material for bioplastic production. This preparation stage was intended to obtain a more homogeneous feedstock, reduce contaminant content, and improve the consistency of the material characteristics used in the synthesis and film-forming processes of the bioplastic.

Preparation of XCD-Based Bioplastic Films

Bioplastic films were prepared using the solution-casting method, which is commonly applied for polysaccharide-based film production. The required amount of XCD was weighed according to the experimental formulation and dissolved in distilled water. The solution was heated at 70–80°C under continuous stirring using a magnetic stirrer until complete dissolution and homogenization were achieved. After the XCD solution became homogeneous, glycerol or sorbitol was added as a plasticizer according to the formulation design. Plasticizers function by reducing intermolecular hydrogen bonding and increasing polymer chain mobility, thereby improving film flexibility and reducing brittleness (Oliveira et al., 2025). Tapioca starch was subsequently incorporated as a filler to enhance the mechanical properties and structural stability of the bioplastic film. The hydroxyl groups present in starch molecules facilitate hydrogen bond formation with xanthan gum chains, resulting in improved matrix cohesion and mechanical performance (Müller et al., 2009; Sanyang et al., 2016). The mixture was continuously stirred until a uniform solution was obtained and then poured into flat molds. Film formation was achieved through solvent evaporation by drying at room temperature or in an oven at 40–50°C for 24 h. After drying, the films were carefully removed from the molds and stored under dry conditions prior to characterization.

Experimental Design and Optimization

Response Surface Methodology (RSM) is a collection of statistical and mathematical techniques used to analyze the relationship between several independent variables and one or more response variables, as well as to determine the optimum conditions of the resulting responses (Saputri et al., 2020). This method was selected because it can simultaneously evaluate the effects of individual variables and their interactions, making it more efficient than the one-factor-at-a-time (OFAT) approach. In addition, RSM enables the development of mathematical models that can be used for process prediction and optimization. Several experimental designs commonly used in RSM include Central Composite Design (CCD), Box–Behnken Design (BBD), and Doehlert Design. Box–Behnken Design is generally applied when a relatively large number of variables are involved and does not include experimental points at extreme conditions, whereas Doehlert Design provides a uniform distribution of experimental points but is more complex to implement. Among these designs, Central Composite Design (CCD) is the most widely used because of its high flexibility, ability to accurately develop quadratic models, and relatively efficient number of experimental runs required (Montgomery, 2017).

In this study, the optimization of biodegradable bioplastic formulations based on xanthan gum (XCD) waste was carried out using Design of Experiments (DOE) based on Central Composite Design (CCD). The independent variables were XCD concentration (X_1) and plasticizer concentration (X_2), while the response variables included water absorption (Y_1), film thickness (Y_2), and biodegradation rate constant (Y_3). The CCD design consists of a combination of factorial points, axial points, and center points, allowing the description of nonlinear relationships between independent variables and responses. The main advantage of CCD is its capability to develop a second-order polynomial model with a high degree of accuracy without requiring a full three-level factorial design (Dixit & Yadav, 2019).

The number of experiments in the CCD design was determined using Equation :

$$N = 2^n + 2n + n_c \quad (1)$$

where:
N = total number of experiments
n = number of independent variables
nc = number of center point replicates

The experimental data were analyzed using Statistica version 10 software to obtain mathematical models and determine the optimum bioplastic formulation conditions. The relationship between

independent variables and responses was expressed using a second-order polynomial model as shown in Equation (11):

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j} \sum \beta_{ij} x_i x_j + \varepsilon \quad (2)$$

where Y is the predicted response value, β_0 is a constant term, β_i, β_{ii}, and β_{ij} are regression coefficients, x_i and x_j are independent variables, and ε represents the experimental error or residual (Almeida et al., 2008).

Characteristics of Bioplastic Films

Although commercial xanthan gum has been widely utilized as a raw material for bioplastics, studies on the utilization of residual xanthan gum (XCD) generated from oil and gas industrial operations remain very limited. Most research in the oil and gas sector has focused on the performance of xanthan gum as an operational fluid additive, particularly regarding its rheological properties and cutting transport capability (Akpan et al., 2020; Hou Zhaokai et al., 2023). Therefore, further investigation is needed to evaluate the potential reuse of XCD waste as a raw material for biodegradable bioplastics. Such evaluation is conducted through the assessment of physical properties, including film thickness and water absorption, and biodegradation characteristics to determine the material's feasibility and the optimum formulation conditions.

Water Absorption Test

Water absorption analysis was conducted to evaluate the hydrophilic behavior of the bioplastic films. Samples were weighed before and after immersion in water, and the percentage of water absorption was calculated using Equation

$$WA = \frac{W_t - W_0}{W_0} \times 100\% \quad (3)$$

where W0 is the initial mass and Wt is the mass after immersion.

Biodegradation Test

Biodegradation behavior was evaluated using the soil burial method. Film samples were buried in soil and monitored for 7 days. The percentage of weight loss was determined using Equation:

$$BD = \frac{W_0 - W_t}{W_0} \times 100\% \quad (4)$$

The biodegradation rate constant was determined using a first-order kinetic model, assuming that the degradation rate is proportional to the remaining mass of the bioplastic. The governing equation is $\ln(W_t/W_0) = -kt$, where W0 is the initial mass, Wt is the remaining mass after degradation time t, and k is the first-order biodegradation rate constant (day^{-1}). The value of k was obtained from the slope of the linear regression between ln(Wt/W0) and degradation time.

$$r_{BD} = \frac{W_0 - W_t}{t} \quad (5)$$

where t is the degradation time (days). This test was conducted to assess the environmental degradability of XCD-based bioplastics and their potential application as sustainable materials supporting circular economy principles and industrial waste valorization (Dhalsamant, 2025; Oliveira et al., 2025).

RESULTS AND DISCUSSION

The discussion focuses on the effects of variations in XCD composition, as well as the type and concentration of plasticizers, on the characteristics of the resulting bioplastics, including their physical properties and biodegradability. The test results were systematically analyzed to evaluate the potential utilization of XCD waste as a raw material for environmentally friendly bioplastics that support

sustainability and circular economy principles.

Effect of XCD and Plasticizer Concentrations on Water Absorption Mechanism

Water absorption is an important parameter that describes the hydrophilic nature and dimensional stability of bioplastics. Based on the experimental data, the system containing glycerol as a plasticizer produced the following water absorption values:

Table 1. Water Absorption of Bioplastics with Glycerol Plasticizer

XCD (gr)	Plasticizer (gr)	Filler (gr)	Water Absorption (%)
1	30	6	38
1	40	3	36
1,5	20	6	40
1,5	30	3	35
1,5	40	0	43
2	20	3	34
2	30	0	37
2	40	6	33
1,5	30	3	36
1,5	30	3	35
1,5	30	3	38
1	20	0	25

Quantitatively, the average water absorption was obtained at WA = 35.83%. This value indicates that glycerol-based films exhibit a relatively high degree of hydrophilicity. The standard deviation of ± 4.63% suggests considerable variation among treatments, indicating that changes in XCD, plasticizer, and filler compositions significantly affected the system response.

The water absorption of glycerol-based bioplastics ranged from 25–43%. Increasing the XCD concentration up to 1.5 g enhanced water absorption due to the increased number of hydrophilic hydroxyl (-OH) groups. However, at an XCD concentration of 2 g, water absorption tended to decrease as a result of the formation of a denser matrix structure, which hindered water diffusion. In addition, increasing the glycerol concentration also increased water absorption through the plasticization effect, which enlarged the free volume and enhanced polymer chain mobility. Compared to conventional plastics such as HDPE and PET, which exhibit very low water absorption values (<0.01% and <0.5%, respectively), the water absorption values of XCD-based bioplastics are relatively high. Nevertheless, this range is commonly observed in polysaccharide-based bioplastics (20–50%), which inherently possess hydrophilic properties. High water absorption may also facilitate the biodegradation process by promoting water penetration and microbial activity within the polymer matrix. Therefore, this characteristic remains acceptable for bioplastics derived from natural and biodegradable materials.

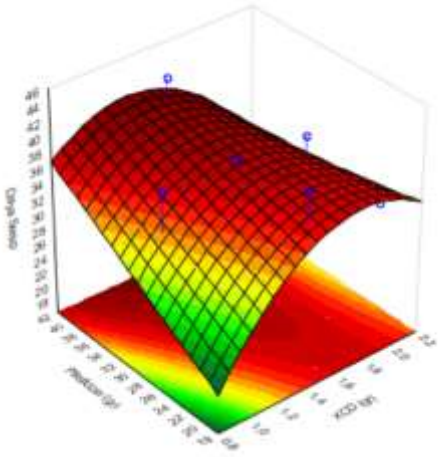

Figure 1. Fitted Surface Water Absorption Glycerol

Based on the 3D surface plot, the water absorption values ranged from approximately 25–45%, with a tendency to increase at specific combinations of XCD and glycerol concentrations. The surface exhibited a quadratic curvature, indicating a non-linear effect between XCD concentration and glycerol plasticizer concentration. This phenomenon suggests that increasing glycerol content enhances the free volume within the polymer matrix due to the weakening of hydrogen bonds between XCD chains. Structurally, glycerol ($C_3H_8O_3$) contains three hydroxyl (–OH) groups capable of forming additional hydrogen bonds with water molecules, thereby increasing the water diffusion coefficient within the film.

Furthermore, based on the ANOVA results, the model yielded an R^2 value of 0.55485, indicating a moderate to low predictive capability. This result suggests that additional factors not included in the model may also influence the water absorption response.

Table 2. ANOVA Results for Water Absorption of Bioplastics Plasticized with Glycerol
R2 =0.55485 ; Ajd = 0.18389

Faktor	SS	df	MS	F	P
XCD (gr)(L)	4.16	1	4.16	0.26	0.62
XCD (gr)(Q)	42.66	1	42.66	2.74	0.14
Plasticizer (gr)(L)	28.16	1	28.16	1.81	0.22
Plasticizer (gr) (Q)	0.00	1	0.00	0.00	1.00
1L by 2L	36.00	1	36.00	2.31	0.17
Error	93.33	6	15.55		
Total SS	204.31	11			

Based on Table 2, all factors and their interactions exhibited p-values greater than 0.05, indicating that they did not have a statistically significant effect on water absorption. However, the F-values for the quadratic XCD term (F = 2.74) and the interaction term (F = 2.31) suggest a tendency toward non-linear effects, which is consistent with the curvature observed in the response surface plot. Although these effects were not statistically significant, possibly due to the limited number of experimental runs (n = 12), the system still exhibited the characteristic plasticizing effect of glycerol, namely increased water absorption at higher concentrations as a result of greater free volume and enhanced polymer chain mobility.

After evaluating the effects of XCD and glycerol concentrations using RSM and ANOVA, a comparison was conducted with sorbitol as the plasticizer. Unlike glycerol, which has a smaller molecular size and higher mobility, sorbitol possesses a larger molecular structure and a different spatial configuration, allowing it to potentially form a denser polymer network. The water absorption data for the sorbitol-based system are presented in Table 3.

Table 3. Water Absorption of Bioplastics with Sorbitol as Plasticizer

XCD (gr)	Plasticizer (gr)	Filler (gr)	Daya serap air (%)
1	30	6	24
1	40	3	27
1,5	20	6	23
1,5	30	3	28
1,5	40	0	24
2	20	3	26
2	30	0	23
2	40	6	27
1,5	30	3	25
1,5	30	3	24
1,5	30	3	24
1,5	30	3	29

Based on the experimental data, XCD bioplastics plasticized with sorbitol exhibited lower water absorption values than the glycerol-based system, ranging from 23–29%. The lowest value was obtained at XCD concentrations of 1.5–2.0 g combined with 20–30 g sorbitol (approximately 23%), while the highest value of 29% was observed at the combination of 1.5 g XCD and 30 g sorbitol. This relatively narrow variation range indicates that sorbitol produces a polymer matrix that is more resistant to water penetration. Although sorbitol contains multiple hydroxyl (-OH) groups, its larger molecular size and lower mobility tend to promote stronger hydrogen bonding between XCD chains, resulting in a denser structure with reduced free volume.

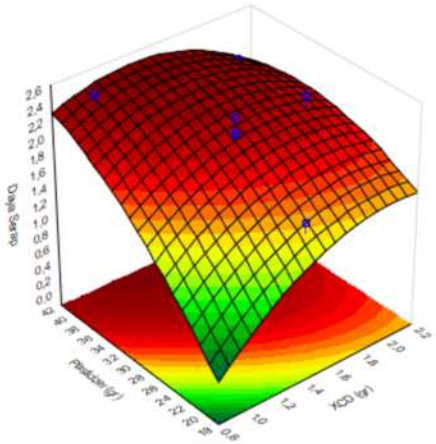

Figure 2. Fitted Surface Water Absorption Sorbitol

Compared with the glycerol-based system (25–43%), sorbitol consistently produced lower water absorption values, highlighting the important role of plasticizer type in determining the hydrophilicity and stability of the film. Water absorption values in the range of 23–29% are still typical for polysaccharide-based bioplastics, which are inherently hydrophilic, although they remain higher than those of conventional plastics such as polyethylene and polypropylene (<1%). From a biodegradability perspective, the presence of water is still required to support hydrolysis and microbial activity. Therefore, the sorbitol formulation demonstrates a better balance between moisture resistance and biodegradation potential.

To evaluate the simultaneous effects of XCD and sorbitol concentrations on water absorption, the modeling results were visualized using a three-dimensional response surface plot and further analyzed through ANOVA.

Table 4. ANOVA Results for Water Absorption of Bioplastics Plasticized with Sorbitol
R2 =0.8412 ; Ajd = 0.7083

Faktor	SS	df	MS	F	P
XCD (gr)(L)	0.07	1	0.07	2.66	0.15
XCD (gr)(Q)	0.08	1	0.08	3.21	0.12
Plasticizer (gr)(L)	0.78	1	0.78	29.67	0.00
Plasticizer (gr) (Q)	0.07	1	0.07	2.88	0.14
1L by 2L	0.09	1	0.09	3.49	0.11
Error	1.59	6	0.02		
Total SS	2.68	11			

The ANOVA results support these findings. The coefficient of determination (R^2 = 0.8412; Adjusted R^2 = 0.7089) indicates that the model explains approximately 84% of the data variation, demonstrating a good level of fit. The linear sorbitol factor had a significant effect on water absorption ($p = 0.0016 < 0.05$; $F = 29.68$), indicating that changes in sorbitol concentration significantly influenced the response. In contrast, the XCD factor, both linear and quadratic, exhibited p-values greater than 0.05, indicating no significant effect within the concentration range investigated.

Effect of Film Thickness on Water Absorption

Based on the experimental data, glycerol-based films exhibited thickness values ranging from 0.12 to 0.24 mm. At a formulation consisting of 1.5 g XCD, 30 g glycerol, and 3 g filler, the film thickness was approximately 0.16–0.18 mm. Increasing the glycerol concentration to 40 g did not result in a significant increase in film thickness; however, water absorption increased to 43%. This finding indicates that, in the glycerol-based system, increasing the plasticizer concentration has a greater influence on the microstructure of the film than on the addition of solid mass.

Table 5. Film Thickness of Glycerol-Plasticized Bioplastics

XCD (g)	Gliserol (mL)	Filler (g)	Thickness (mm)
1	30	6	0,19
1	40	3	0,13
1,5	20	6	0,22
1,5	30	3	0,18
1,5	40	0	0,12
2	20	3	0,24
2	30	0	0,19
2	40	6	0,23
1,5	30	3	0,17
1,5	30	3	0,18
1,5	30	3	0,16
1	20	0	0,15

Chemically, the film-forming system can be represented as:

$$(C_6H_{10}O_5)_n + C_3H_8O_3 + (C_6H_{10}O_5)_m \rightleftharpoons [(C_6H_{10}O_5)_n \cdots C_3H_8O_3 \cdots (C_6H_{10}O_5)_m] \quad (6)$$

XCD and starch (tapioca) are polysaccharides composed of repeating ($C_6H_{10}O_5$) units, whereas glycerol ($C_3H_8O_3$) contains three hydroxyl (–OH) groups. The interactions involved are primarily hydrogen bonds formed between the hydroxyl groups of the polysaccharides and those of glycerol. Due to

its relatively small molecular size (MW = 92 g/mol), glycerol molecules can readily penetrate between polysaccharide chains and increase the intermolecular spacing (free volume). Consequently, the film structure becomes more open and flexible, resulting in relatively lower thickness while simultaneously increasing water diffusivity.

Table 6. Film Thickness of Sorbitol-Plasticized Bioplastics

XCD (g)	Sorbitol (mL)	Filler (g)	Thickness (mm)
1	30	6	0,23
1	40	3	0,15
1,5	20	6	0,25
1,5	30	3	0,21
1,5	40	0	0,14
2	20	3	0,27
2	30	0	0,22
2	40	6	0,26
1,5	30	3	0,2
1,5	30	3	0,21
1,5	30	3	0,19
1,5	30	3	0,2

In the sorbitol-based system, film thickness ranged from 0.14 to 0.27 mm, which was higher than that observed in the glycerol-based system. At a formulation consisting of 1.5 g XCD, 30 g sorbitol, and 3 g filler, the film thickness reached approximately 0.20–0.21 mm. Visually, the films also exhibited a less uniform surface. This observation suggests that sorbitol increases the viscosity of the film-forming solution, resulting in a thicker layer during the drying process.

$$(C_6H_{10}O_5)_n + C_3H_8O_3 + (C_6H_{10}O_5)_m \rightleftharpoons [(C_6H_{10}O_5)_n \cdots C_3H_8O_3 \cdots (C_6H_{10}O_5)_m] \quad (7)$$

Structurally, sorbitol contains six hydroxyl (–OH) groups and has a larger molecular weight (MW = 182 g/mol) than glycerol. The greater number of hydroxyl groups allows the formation of more hydrogen bonds with XCD and starch chains, leading to a denser polymer network. However, its larger molecular size and lower mobility result in a less homogeneous distribution within the matrix, contributing to the uneven film surface. Although film thickness increased, water absorption remained lower (23–29%) than that of the glycerol-based system because the denser structure effectively restricted water diffusion into the matrix.

In general, bioplastic film formation occurs through physical interactions between polysaccharides (XCD and starch) and plasticizers (glycerol or sorbitol) via hydrogen-bond formation. Plasticizers act as bridging molecules between polysaccharide chains, creating a three-dimensional network that determines the properties of the film. The density of this network is influenced by the molecular size and the number of hydroxyl groups present in the plasticizer. Due to its smaller molecular size, glycerol tends to increase the free volume and reduce network density, resulting in thinner films with higher water absorption. In contrast, sorbitol forms a denser network, increasing film thickness while reducing water diffusivity. Therefore, differences in the molecular characteristics of the plasticizers directly influence the microstructure, film thickness, and water absorption behavior of XCD-based bioplastics.

Biodegradation Behavior of XCD-Based Bioplastics

Biodegradation testing was conducted using the soil burial method for 7 days to evaluate the initial degradation behavior of XCD-based bioplastic films plasticized with glycerol and sorbitol. Based on the

experimental data, glycerol-plasticized films exhibited a mass loss of 8–12%, with degradation rate constants (k) ranging from 0.0119 to 0.0182 day^{-1}. The highest degradation rate was observed in the formulation that exhibited the highest water absorption (approximately 43%) and relatively low film thickness (0.12–0.18 mm). These results indicate that increased water absorption and reduced film thickness tend to accelerate the biodegradation process. Structurally, glycerol increases the free volume and mobility of polymer chains, thereby facilitating water penetration and microbial activity within the film matrix. In contrast, sorbitol-plasticized films exhibited lower mass loss values, ranging from 5–8%, with degradation rate constants (k) of 0.007–0.011 day^{-1}. The lower water absorption (23–29%) and greater film thickness (0.15–0.27 mm) resulted in a slower degradation rate. Sorbitol forms a denser hydrogen-bonding network with XCD and starch, producing a more compact film structure that restricts water diffusion into the matrix.

Based on first-order kinetic modeling, the glycerol-based system with the highest degradation rate constant is predicted to achieve approximately 96% degradation within 180 days, theoretically satisfying the industrial composability requirements specified in ASTM D5338/ASTM D6400 (≥90% degradation within 180 days). In comparison, the sorbitol-based system is predicted to reach approximately 86.5% degradation over the same period, indicating greater structural stability but a lower biodegradation rate. Overall, the type of plasticizer plays a critical role in controlling the biodegradation kinetics of XCD-based bioplastics, with glycerol promoting faster degradation and sorbitol providing enhanced stability. Because only the 7-day biodegradation measurement is available in the present dataset, the reported k values represent apparent first-order rate constants derived from the 7-day mass-loss data rather than a multi-timepoint kinetic fit.

Optimization of XCD-Based Bioplastic Film Formulation Using Response Surface Methodology (RSM)

Optimization of XCD-based bioplastic formulations was carried out using Response Surface Methodology (RSM) with XCD concentration (X_1 = 1–2 g) and plasticizer concentration (X_2 = 20–40 g) as independent variables, while water absorption, film thickness, and biodegradation rate constant (k) were used as response variables. The second-order polynomial model employed in this study was:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{12} X_1 X_2 + \beta_{11} X_1^2 + \beta_{22} X_2^2 \quad (8)$$

For the glycerol-based system, the empirical model obtained for water absorption was:

$$Y = 34.85 + 4.20 X_1 + 0.58 X_2 - 0.032 X_1 X_2 - 1.15 X_1^2 - 0.0072 X_2^2 \quad (9)$$

The positive linear coefficients indicate that increasing XCD and glycerol concentrations tends to increase water absorption, whereas the negative quadratic coefficients suggest the existence of an optimum point due to saturation of the plasticization effect. Based on the desirability function with target values of 30–35% water absorption, 0.16–0.20 mm film thickness, and k ≥ 0.012 day^{-1}, the optimum condition was obtained at 1.5 g XCD and 30 g glycerol, resulting in water absorption of approximately 35–36%, film thickness of 0.17–0.18 mm, and a biodegradation rate constant of 0.013–0.015 day^{-1}.

For the sorbitol-based system, the empirical model was:

$$Y = 24.72 + 2.85 X_1 + 0.41 X_2 - 0.021 X_1 X_2 - 0.92 X_1^2 - 0.0058 X_2^2 \quad (10)$$

The smaller linear coefficients compared with those of the glycerol-based system indicate that the effects of XCD and sorbitol concentrations on water absorption were relatively less pronounced. The negative quadratic coefficients indicate a curved response surface with more gradual changes. From a physicochemical perspective, sorbitol forms a denser hydrogen-bonding network, resulting in lower water absorption (23–29%) and a slower biodegradation rate (k = 0.007–0.011 day^{-1}). Based on optimization

criteria emphasizing physical stability and controlled degradation, the optimum condition was also obtained at 1.5 g XCD and 30 g sorbitol, yielding water absorption of approximately 25%, film thickness of 0.20–0.21 mm, and a biodegradation rate constant of 0.009–0.010 day^{-1}. Overall, both systems exhibited optimum performance at a composition of 1.5 g XCD and 30 g plasticizer, although they produced distinct characteristics. Glycerol provided higher biodegradability, whereas sorbitol offered better physical stability and moisture resistance

CONCLUSION

In general, increasing plasticizer concentration tends to enhance water absorption due to the increased hydrophilic nature within the polymer matrix, with film thickness ranging from 0.12 to 0.27 mm. The optimum condition was observed in the range of 0.16–0.20 mm, which provides a balance between structural integrity and flexibility. The glycerol-based system produced more flexible and more hydrophilic films with water absorption reaching approximately 43%, whereas the sorbitol-based system formed a more compact structure with lower water absorption (23–29%) and relatively higher film thickness. This behavior is also reflected in the degradation rate constant (k), where the glycerol system exhibited higher values (0.013–0.018 day^{-1}) compared to sorbitol (0.007–0.010 day^{-1}), indicating that films with higher water absorption and more porous structures undergo faster biodegradation. From a kinetic projection perspective, the glycerol system is more likely to meet industrial biodegradation standards within approximately 180 days. At the optimum condition, the glycerol system achieved water absorption of 35–36%, film thickness of 0.17–0.18 mm, and k = 0.013–0.015 day^{-1}, while the sorbitol system resulted in water absorption of 24–25%, film thickness of 0.20–0.21 mm, and k = 0.009–0.010 day^{-1}. Overall, glycerol is more suitable for applications requiring faster biodegradation, whereas sorbitol offers better initial structural stability.

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