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Characteristics of Bioplastic Composites on Variations in Taro Starch (*Colocasia esculenta*)-Carrageenan Ratio and Polycaprolactone Reinforcing Agent Concentration

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Abstract. *Using petroleum-based plastics presents significant environmental challenges due to their difficulty in decomposition. This study explores the characteristics of bioplastic composites created from taro starch (Colocasia esculenta) and carrageenan, incorporating polycaprolactone (PCL) as a reinforcing agent. An experimental approach was employed, varying the ratio of taro starch to carrageenan (25:75 and 50:50) and the concentration of PCL (7.5%, 10%, 12.5%, and 15%). The evaluation included tests for tensile strength, elongation at break, elasticity, thickness swelling, and biodegradation. The results showed that the variation of the ratio of taro starch: carrageenan affected tensile strength, elasticity, and biodegradation but not elongation at break and swelling. In comparison, PCL reinforcement affected elongation at break and swelling but not tensile strength, elasticity, and biodegradation. Bioplastic composite with a ratio of taro starch: carrageenan of 25:75 and a concentration of PCL reinforcement of 12.5% (0.75 g) with a tensile strength value of 10.37 ± 2.57 MPa; elongation at break of 2.11 ± 10%; elasticity of 520.07 ± 123.47 MPa; swelling of 70.18 ± 4.96% and the duration of biodegradation on the 5th day. FTIR analysis confirmed the presence of C-H, C-O, C=O, and O-H functional groups, indicating compatibility among the materials in forming the bioplastic composites. The results of this study suggest that bioplastics derived from taro starch and carrageenan, supplemented with PCL, could serve as a promising alternative for environmentally friendly packaging that biodegrades more effectively than traditional plastics.*
Keywords: *bioplastic; taro starch; carragenan; polycaprolactone; biodegradable.*

Type of the Paper: Regular Article.

1. Introduction

Plastic is an integral part of modern life, valued for its durability and cost-effectiveness [1]. However, using plastic as a packaging material presents significant environmental challenges, such as its production from non-renewable petroleum sources and the accumulation of plastic waste that is neither recyclable nor biodegradable by soil microorganisms [2]. In light of these issues, the development of bioplastics offers a promising alternative solution. Bioplastic is an environmentally friendly alternative to traditional plastics, easily decomposed by microorganisms while providing the same utility value as standard plastics [3]. Bioplastics can be produced by manufacturing natural materials derived from plants or animals and may incorporate a blend of natural and synthetic components. Taro tuber starch is an ideal raw material for bioplastic

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production, as it decomposes 10 to 20 times faster and is readily biodegradable. Furthermore, Indonesia yields around 28 tons per hectare of taro tubers [4]. Taro is easily cultivated in Indonesia and reaches harvest readiness in 6 to 8 months, indicated by the yellowing of leaves. The substantial production of taro tubers in Indonesia presents an excellent resource for bioplastic manufacturing, potentially enhancing both the agricultural sector and environmental sustainability [5].

Research conducted by Hartiati et al. [6] revealed that a composite of cassava starch and carrageenan, with a starch-to-carrageenan ratio of 25:75, achieved a tensile strength of 27.35 MPa, an elongation at break of 18.01%, and an elasticity of 151.94 MPa. According to this study, the tensile strength value meets the criteria outlined in SNI 7188.7: 2016, although the elongation at break and elasticity do not satisfy the specified requirements. Additionally, a study by Wara et al. [7] found that a composite of "gadung" starch and carrageenan, using a 50:50 starch-to-carrageenan ratio, yielded the most favorable results, with a tensile strength of 3.60 MPa, an elongation at break of 25.373%, and an elasticity of 14.219 MPa. This study concluded that the elongation at break meets the standards outlined in SNI 7188.7: 2016, while the tensile strength and elasticity fall short of the requirements. The results of this study indicate that bioplastics from various types of materials and formulations produce varying characteristics with low tensile strength and elasticity. Research on adding reinforcing agents needs to be carried out in this regard.

Various reinforcing or filler materials from organic, inorganic, and nanostructured carbon materials have been reported. Organic nanofillers also include biopolymers such as chitosan and cellulose; at the same time, inorganic nanofillers can be metals (silver, gold) or metal oxides (ZnO, TiO2) [8]. In addition, reinforcing materials commonly used in the manufacture of bioplastics are PVA and PCL. The application of PVA has been demonstrated in studies by Sipayung et al. [9]. However, using PCL as a reinforcing material is not as prevalent. Notably, Hasibuan et al. [10] employed 15% polycaprolactone (PCL) as a novel reinforcer in creating cornstarch-glucomannan composites. This formulation yielded favorable results, achieving a tensile strength of 16.16 MPa, elongation at break of 2.620%, elasticity of 627 MPa, and a biodegradation time of 7.33 days. Despite these outcomes, the study failed to meet specific SNI requirements, except for biodegradation. However, the study's results, except for biodegradation, still do not meet SNI requirements. Concerning this, this study has tried to use other composite materials, namely taro starch: carrageenan ratio 25:75 [6] and ratio 50:50 [7] with PCL reinforcing material [10], to improve the characteristic values of bioplastic composites to meet SNI requirements. Only a limited number of variables have met the criteria from prior research, including tensile strength, elongation at break, and degradation time. Consequently, the elasticity variable does not fulfill the SNI bioplastic standard SNI 7188.7: 2016. This study aims to develop a bioplastic composite made

from taro starch (Colocasia esculenta) and carrageenan, incorporating PCL reinforcement to improve the variables that do not comply with SNI bioplastic requirements.

2. Materials and methods

2.1. Place and Time of Research

The production of starch and bioplastic composites, along with the thickness expansion test, was conducted at the Biochemistry and Nutrition Laboratory of the Faculty of Agricultural Technology at Udayana University. The biodegradation test took place in the same faculty's greenhouse. The tensile strength, elongation at break, and elasticity tests were also conducted at the Post-harvest Laboratory of the Faculty of Agricultural Technology, Udayana University. This research was conducted between February and April 2024.

2.2. Materials

The materials utilized in this study included both raw materials and chemicals. The raw materials were sourced from the Badung market, specifically taro tubers, and carrageenan was obtained from Planet Kimia Depok. The substances employed in the study consisted of Polycaprolactone (PCL), maleic acid glycerol, and distilled water procured from UD Saba Kimia Denpasar.

The equipment used in this research encompassed knives, cutting boards, basins, blenders, filter paper, filter cloth, ovens, 80 mesh sieves, dropper pipettes, stirring rods, analytical balances, 100 ml beakers, hot plates, thermometers, Teflon molds with a diameter of 20 cm, plastic pots, and plastic mechanical testing apparatuses according to ASTM specifications D638, as well as FTIR spectrometers.

2.3. Experimental Design

This study employed a two-factor Randomized Block Design (RAK). The first factor was the ratio of taro starch to carrageenan, with two levels consisting of 6 g of raw materials: 1.5 g of taro starch to 4.5 g of carrageenan and 3 g of each. The second factor involved the concentration levels of the polycaprolactone strengthening material, which included four levels: 7.5%, 10%, 12.5%, and 15%. As detailed in Table 1, this design resulted in 8 treatment combinations, each assigned to 2 processing times for preparing taro starch-carrageenan bioplastic composites, leading to 16 experimental units.

Table 1. Experimental design treatment for making bioplastic composites

No	Raw material treatment (taro starch: carrageenan ratio)	Polycaprolactone concentration (%)			
		7.5% (S1)	10% (S2)	12.5% (S3)	15% (S4)
1.	25:75 (P1)	P1S1	P1S2	P1S3	P1S4
2.	50:50 (P2)	P2S1	P2S2	P2S3	P2S4

2.4. Taro Starch Production

Making taro starch begins with peeling the peel off the tuber and thoroughly washing it until it is clean. The taro tuber is then cut into small pieces, approximately 3 cm in size. These pieces are soaked in water for about 20 minutes to eliminate the sap present in the taro. After washing, the taro is pureed using a blender and filtered through a cloth to obtain the liquid filtrate, which is left to sit for 24 hours. After this period, a layer of starch settles at the bottom, separating it from the water. The wet starch is then dried in an oven at a temperature of 80°C for four hours. Once dried, the starch is blended and passed through an 80-mesh sieve. This method of making taro starch is based on research conducted by Permana et al. [11].

2.5. Bioplastic Composite Manufacturing Process

The bioplastic manufacturing process involves weighing taro starch and carrageenan with two different ratios: 1.5 g of taro starch to 4.5 g of carrageenan and 3 g of taro starch to 3 g of carrageenan. The total amount of taro starch and carrageenan used in each treatment is 6 g. Next, 5% maleic acid anhydride is measured, and PCL is included at concentrations of 10%, 12.5%, 15%, and 17.5% of the total mixture. All weighed materials are combined in a beaker and dissolved in 1% acetic acid until a total weight of 100 g is achieved. Each dissolution occurs in separate beakers simultaneously, and the mixture is heated for 15 minutes at 75 °C and continuously stirred with a rod until homogeneous. Following dissolution, the materials are merged in a single beaker and gelatinized on a hot plate at a temperature of 75±2°C for 10 minutes, with temperature monitoring using a thermometer. Once homogeneous, a 1% plasticizer is added. The mixture, which includes the gelatinized taro starch, carrageenan with maleic acid anhydride, glycerol, and PCL, is then formed in a 20 cm Teflon mold and dried in an oven at 50±1°C for 12 hours. After drying, the molded bioplastic is removed from the oven and allowed to cool at room temperature for 24 hours until it can be detached from the mold. This method of producing the bioplastic composite is a modification of the research conducted by Hasibuan et al. [10] incorporating changes to the composite materials used.

2.6. Observed Variables

The observed variables are tensile strength (SNI 7188.7: 2016), elongation at break (SNI 7188.7: 2016), elasticity (Young's Modulus) (SNI 7188.7: 2016), swelling (SNI 7188.7: 2016), biodegradation (ASTM D638), and determination of functional groups using Fourier Transform InfraRed Spectroscopy [12].

3. Results and Discussion

3.1. Tensile Strength

The variance analysis results indicated that variations in the ratio of taro starch to

carrageenan, as well as the concentration of polycaprolactone reinforcement, and their interaction, had a highly significant effect ($p<0.01$) on the tensile strength of the bioplastic composite. A higher tensile strength value reflects the material's ability to endure applied forces. Consequently, an increased tensile strength indicates enhanced protection for the product against mechanical factors such as physical pressure, vibration, and impacts among materials [13]. As shown in Table 2, the taro starch: carrageenan bioplastic composite with a 12.5% concentration of polycaprolactone reinforcement at a 50:50 ratio achieved the highest tensile strength value of 10.55±6.71 MPa. This highlights that the amount of polycaprolactone reinforcement used plays a crucial role in the properties of the resulting bioplastic. Several research results with various types of raw materials and process conditions show differences in the tensile strength of bioplastics, including bioplastics from belitung taro starch (*Xanthosoma sagittifolium*) and carrageenan, producing a tensile strength of 3,210 ± 0.125 MPa [14], cornstarch-glucomannan 16.16 MPa [10], gadung tuber starch-ZnO 1.385 ± 0.007 MPa [15], thermoplastic starch-thermoplastic glucomannan-polylactic acid 30.43 MPa [16], cornstarch-glucomannan-glycerol 5.685 MPa [17], and cornstarch-ZnO 11 MPa [18]. Differences in the types of materials and production process conditions cause the differences in the characteristics of these bioplastics.

Table 2. Average tensile strength (MPa) of bioplastic composites

Starch: carrageenan (g)	Polycaprolactone Concentration (%)			
	7.5%	10%	12.5%	15%
25:75	3.32±0.61^{e}	7.36±1.21^{bc}	10.37±2.57^{ab}	6.18±1.43^{c}
50:50	4.12±2.92^{d}	4.47±0.41^{d}	10.55±6.71^{a}	5.20±0.94^{c}

Note: Different letters after the mean value indicate significant differences at the 5% error level ($p<0.05$).

3.2. Elongation at Break

The results of the variance analysis indicate that neither the variation in the taro starch: carrageenan ratio nor their interaction yields a significant effect. In contrast, the concentration of the polycaprolactone reinforcer has a markedly substantial impact ($p<0.01$) on the elongation at break of the resulting bioplastic composite. The resulting elongation at break values ranged between 2.11±1 - 4.97±1.05%. Elongation at break refers to the percentage increase in length of the bioplastic sample from the start of the tensile test until rupture. Table 3 demonstrates that the bioplastic composite made with a taro starch: carrageenan treatment ratio of 50:50 and a polycaprolactone concentration of 7.5% achieves the highest elongation at break value of 4.97±1.05%. This result is not significantly different from that of the treatment ratio of 25:75 with a polycaprolactone concentration of 7.5% (0.9 g), as well as the treatment including a stearic acid plasticizer concentration of 15%, which yielded an elongation at break of 4.27±2.05%. Several research results with various types of raw materials and process conditions show differences in the elongation at break strength of bioplastics, including bioplastics from belitung taro starch

(*Xanthosoma sagittifolium*) and carrageenan producing 20.7 ± 0.038% [14], cornstarch-glucomannan 2.620% [10], gadung tuber starch-ZnO 0.102 ± 0.014% [15], thermoplastic starch-thermoplastic glucomannan-polylactic acid 0.90% [16], cornstarch-glucomannan-glycerol 20.110% [17], and cornstarch-ZnO 31.16% [18]. Differences in the types of materials and production process conditions cause the differences in the characteristics of these bioplastics.

Table 3. Average value of elongation at break (%) of bioplastic composites

Starch: carrageenan (g)	Polycaprolactone Concentration (%)			
	7.5%	10%	12.5%	15%
25:75	4.27±2.05	2.12±0.98	2.11±0.10	4.27±2.05
50:50	4.97±1.05	2.86±2.02	2.08±0.98	2.12±0.98
Average	4.62±1.55^{a}	2.49±1.51^{b}	2.19±0.54^{b}	3.15±1.52^{b}

Note: Different letters after the mean value indicate significant differences at the 5% error level ($p<0.05$).

3.3. Young's Modulus

The results of the variance analysis indicate that the ratio variation of taro starch to carrageenan and the concentration of polycaprolactone reinforcer have a highly significant effect ($p<0.01$). Conversely, their interaction significantly impacts ($p<0.05$) the elasticity of bioplastic composites made from taro starch and glucomannan. As shown in Table 4, the highest elasticity value (665.06±30.65 MPa) for the taro starch and carrageenan bioplastic occurs at a 50:50 ratio with a polycaprolactone concentration of 12.5% (0.9 g). This value significantly differs from the treatment involving a 25:75 ratio and a polycaprolactone concentration of 15%, yielding an elasticity of 172.93±16.48 MPa. Furthermore, the combination of a 25:75 ratio with a polycaprolactone concentration of 7.5% results in the lowest average elasticity value (84.24 ± 6.22 MPa), which does not differ significantly from the treatment with a 50:50 ratio and a polycaprolactone concentration of 7.5%. This indicates that a higher concentration of carrageenan leads to a reduced elasticity value. Notably, the elasticity value is directly proportional to tensile strength and inversely proportional to elongation [19]. Several research results with various types of raw materials and process conditions show differences in Young's modulus, s of bioplastics, including bioplastics from belitung taro starch (*Xanthosoma sagittifolium*) and carrageenan producing 15.912 ± 3.157 MPa [14], cornstarch-glucomannan 627 MPa [10], gadung tuber starch-ZnO 13.995 ± 0.204 MPa [15], thermoplastic starch-glucomannan thermoplastic-polylactic acid 3.38 GPa [16], cornstarch-glucomannan-glycerol 26.735 MPa [17], and cornstarch-ZnO 7.06 MPa [18]. Differences in the types of materials and production process conditions cause the differences in the characteristics of these bioplastics.

Table 4. Average elasticity value (MPa) of bioplastic composites

Starch: carrageenan (g)	Polycaprolactone concentration (%)			
	7.5%	10%	12.5%	15%
25:75	84.24±6.22^{d}	373.57±15.63^{b}	520.07±23.47^{ab}	172.93±16.48^{cd}
50:50	91.25±8.14^{d}	285.90±76.73^{bc}	665.06±30.65^{a}	215.45±16.71^{bcd}

Note: Different letters after the mean value indicate significant differences at the 5% error level ($p<0.05$).

3.4. Swelling

The results of the variance analysis indicate that neither the variation in the taro starch to carrageenan ratio nor the interaction between these two components has a significant effect on the outcomes. In contrast, the concentration of polycaprolactone reinforcer significantly influences ($p<0.01$) the thickness development of the bioplastic composite derived from taro starch and carrageenan. According to Sulityo and Ismiyati [20], a lower percentage of thickness development correlates with a higher quality of bioplastic, suggesting that a reduction in thickness is desirable. Table 5 illustrates the interactions among the treatments of the bioplastic composite for different taro starch to carrageenan ratios. The 50:50 ratio combined with a 15% polycaprolactone concentration achieved the highest water absorption percentage at 82.67±3.35%. This result is not significantly different from other treatments, except for the 25:75 ratio with a 15% polycaprolactone concentration. Conversely, the lowest water absorption percentage was observed in the 50:50 ratio combined with a 12.5% polycaprolactone concentration, which yielded a value of 43.22 ± 8.08%. This phenomenon can be attributed to starch containing a higher number of hydroxyl groups (OH), which enables it to absorb more water. As the starch concentration increases, so does the water absorption value [21]. Additionally, incorporating polycaprolactone affects the film thickness; as more materials, such as stearic acid, are used in the film-making process, the film's thickness increases, provided the concentration remains optimal. This is because using a greater quantity of materials within the same volume increases total dissolved solids, subsequently leading to a thicker film [22]. Several research results with various types of raw materials and process conditions show differences in the swelling value of bioplastics, including bioplastics from belitung taro starch (*Xanthosoma sagittifolium*) and carrageenan producing 43.695 ± 1.151% [14], cornstarch-glucomannan 30.26% [10], gadung tuber starch-ZnO 13.5 ± 0.007% [15], thermoplastic starch-thermoplastic glucomannan-polylactic acid 0.51% [16], cornstarch-glucomannan-glycerol 1.149% [17], and cornstarch-ZnO 55.01% [18]. Differences in the types of materials and production process conditions cause the differences in the characteristics of these bioplastics.

Table 5. Average value of swelling (%) of bioplastic composites

Starch : carrageenan (g)	Polycaprolactone concentration (%)			
	7.5%	10%	12.5%	15%
25:75	61.36±6.07^{ab}	50±0.00^{bc}	70.18±4.96^{a}	62.28±6.20^{ab}
50:50	64.29±3.57^{ab}	65.51±3.80^{ab}	43.22±8.08^{c}	82.67±3.35^{a}

Note: Different letters after the mean value indicate significant differences at the 5% error level ($p<0.05$).

3.5. Biodegradation time

Biodegradation measurement aims to determine the time required for bioplastic composites to decompose in the environment. Based on the results of the analysis, it shows that the treatment of the taro starch: carrageenan ratio variation has a significant effect ($p <0.05$). In contrast, the

concentration of polycaprolactone reinforcement and the interaction of both have no significant impact on the resulting bioplastic composite. The biodegradation value of taro and carrageenan bioplastic composites ranges from 5 to 8 days. Table 6 shows that the taro starch possesses a high biodegradation time: carrageenan bioplastic composite with a 50:50 ratio treatment and a polycaprolactone concentration of 15% (0.9 g), which degraded on the 8th day, which was not significantly different from the treatment of the 25:75 ratio variation and a polycaprolactone concentration of 7.5% (0.45 g) and 10% (0.10 g). Meanwhile, the lowest biodegradation time was found in the taro starch: carrageenan bioplastic composite with a ratio variation treatment of 25:75 and a polycaprolactone concentration of 12.5% (0.75 g) with a biodegradation time of 5 days, which was not significantly different from the ratio variation treatment of 25:75 15% (0.9 g) with a time of 5.5 days. Bioplastic composites are easily degraded because they comprise natural components, namely taro and carrageenan. In addition, bioplastics are also degraded due to the process of breaking down the polymer chain in variations in the ratio of raw materials, namely starch containing hydroxyl (O-H), carbonyl (C=O) and ester (C-O) functional groups into monomers and also the help of microorganisms in the soil [23]. The biodegradation process begins with the hydroxyl group O-H in the starch matrix, which initiates a hydrolysis reaction after absorbing water from the soil. As a result of this hydrolysis reaction, the polymer matrix decomposes into small pieces and quickly disappears in the soil. This reaction will not take long and will not cause environmental pollution [24]. Several research results with various types of raw materials and process conditions show differences in biodegradation time of bioplastics, including bioplastics from gblitung taro starch (*Xanthosoma sagittifolium*) and carrageenan producing 7 days [14], cornstarch-glucomannan 7.33 days [10], thermoplastic starch-thermoplastic glucomannan-polylactic acid 17.67 days [16], cornstarch-glucomannan-glycerol 6 days [17], and cornstarch-ZnO 6-7 days [18]. Differences in the types of materials and production process conditions cause the differences in the characteristics of these bioplastics.

Table 6. Average biodegradation time of bioplastic composites (Days)

Starch: carrageenan (g)	Polycaprolactone concentration (%)			
	7.5%	10%	12.5%	15%
25:75	7.50±0.71^{a}	7.50±0.71^{a}	5.00±0.00^{b}	5.50±0.71^{b}
50:50	7.00±1.41^{ab}	7.00±0.00^{ab}	6.00±1.41^{b}	8.00±0.00^{a}

Note: Different letters after the mean value indicate significant differences at the 5% error level ($p<0.05$).

3.6. Functional groups

Functional groups in bioplastics were identified through infrared absorption data obtained using FTIR. The bioplastics analyzed in this study featured the most effective treatment, consisting of a 50:50 raw material ratio and a 12.5% concentration of polycaprolactone as a reinforcing material, along with taro starch and carrageenan. The results of the FTIR spectroscopy test conducted in this research are illustrated in Fig. 1.

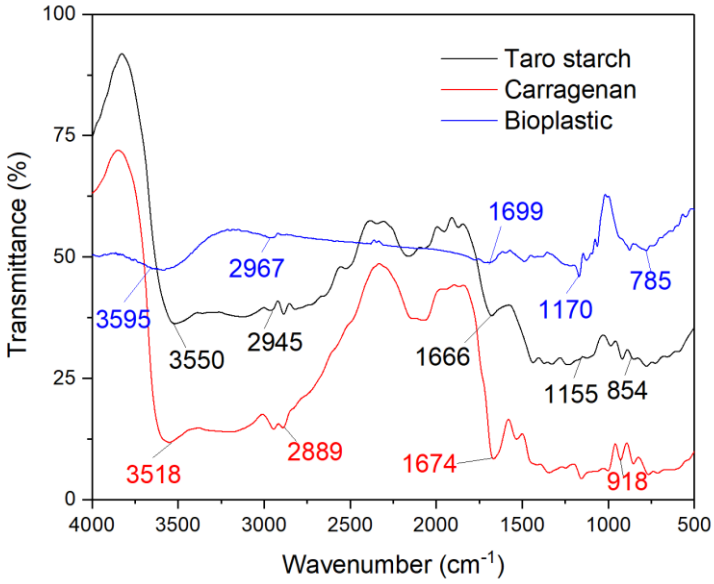

Fig. 1. The results of functional group testing on bioplastic composites with the best values and raw materials

Fig. 1 illustrates the graph depicting the functional group results of the most effective bioplastic composite, which consists of taro starch and carrageenan. The FTIR analysis conducted on microplastics synthesized from taro starch and carrageenan is intended to characterize the chemical composition and assess their structural properties compared to conventional synthetic microplastics. The combined spectrum displayed in the graph depicts the FTIR transmission percentages of three materials: microplastic (blue), taro starch-based bioplastic (red), and carrageenan (black) across a wave number range of 4500–500 cm^{-1}. Variations in transmission highlight the differences in functional groups, polymer bonds, and their potential for biodegradability. The results of the functional group tests indicate that the best bioplastic composite exhibits compatibility with its constituent materials, suggesting that the functional groups from each component can effectively bind together to form a robust bioplastic composite. A comparison of the similarities and differences in the functional groups present in the most effective bioplastic composite and its constituent materials is detailed in Table 7.

Table 7. Absorption areas and functional groups of bioplastic composites

Wavenumber			Absorption area (cm^{-1})	Functional group
Taro starch	Carrageenan	The best bioplastic composite		
854,47;929,69	918.12;985.12	785.06	675-995	C - H
-	1436.97	-	1340-1470	C - H
1155.36	-	1187.24	1050-1300	C - O
1666.5	-	-	1610-1680	C = C
-	-	1699.36	1690-1760	C = O
-	2162.2	-	2100- 2260	C ≡ C
-	-	-	2500-2700	O - H
2945.3	2885.51	2967.61	2850-2970	C - H
3550.95	3518.16	3595.47	3500-3650	O - H

Absorption area source: [12]

Taro starch raw materials are characterized by the presence of fungus groups (C-H) at wave numbers 854.47 and 929.69, alcohol functional groups (C-O) at wave number 1155.36, alkene functional groups (C=C) at wave number 1666.5, alkane functional groups (C-H) at wave number 2945.3, and hydroxyl functional groups (O-H) at wave number 3550.95. In contrast, carrageenan raw materials exhibit C-H functional groups at wave numbers 918.12, 985.12, and 1436.97 and C≡H functional groups at 2162.2. Additionally, C-H functional groups are identified at wave number 2885.51, and O-H functional groups are present at wave number 3518.16. The bioplastic composite of taro starch and carrageenan reveals C-H functional groups at wave number 785.06, C-O functional groups at 1187.24, C=O functional groups at 1699.36, C-H functional groups at 2967.61, and O-H functional groups at 3595.47. These functional groups within the bioplastic composites arise from the starch modification process, known as grafting, which alters the positions of the functional groups [25]. Comparative analysis of FTIR spectra indicates that modifying taro starch and carrageenan during microplastic synthesis leads to structural changes in the polymer. Enhanced C-H and C=O peaks observed in the microplastic spectrum suggest that the modification process improves its hydrophobic properties and resistance to degradation. However, O-H and C-O groups in bioplastic-based microplastics indicate a potential for degradation through hydrolysis and microbial activity, making them more environmentally friendly than petrochemical-based microplastics [26]. Furthermore, there are notable differences in the functional groups of bioplastic composites derived from taro starch, carrageenan, and cellulose acetate, with specific functional groups absent [25]. These findings affirm that taro starch and carrageenan hold significant potential as raw materials for developing more biodegradable microplastics, offering a sustainable solution for mitigating plastic pollution.

4. Conclusions

Based on the conducted research, it can be concluded that variations in the ratio of taro starch to carrageenan and the addition of PCL as a strengthener have a significant effect on tensile strength, elasticity, and biodegradation but do not significantly affect elongation at break or swelling. Adding the plasticizer stearic acid impacts tensile strength, elongation at break, elasticity, and swelling. At the same time, it does not affect the biodegradation of the bioplastic composite made from taro tuber starch and carrageenan. The interaction of the bioplastic composites, considering the variations in the ratio of taro tuber starch to carrageenan and the concentration of polycaprolactone reinforcement, affects the tensile strength and elasticity values. The optimal formulation identified is a bioplastic composite using a 50:50 ratio of taro tuber starch to carrageenan combined with a 12.5% concentration of polycaprolactone reinforcement. This

formulation achieves a tensile strength of 10.55 ± 6.71 MPa, an elongation at break of 2.08 ± 0.98%, elasticity of 665.06 ± 30.65 MPa, and a thickness increase of 82.67 ± 33.35%, with a biodegradation period lasting until day 8. Additionally, FTIR analysis indicates that the bioplastic composite contains alkane (C- H), alkene (C- H), alcohol (C- O), ketone (C = O), and hydroxyl (O- H) functional groups.

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