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Improving Mechanical Properties of Bioplastics from Sweet Potato Peel Waste with CMC and Gum Arabic

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Abstract

Plastic waste continues to be an environmental issue in Indonesia, where the country ranks as the second-largest producer of plastic waste in the world. Bioplastics, derived from renewable materials such as starch, have the potential to serve as an alternative to conventional plastics. The objective of this research is to formulate biodegradable bioplastics utilizing sweet potato peel starch, carboxymethyl cellulose (CMC), and gum Arabic, with glycerol added as a plasticizer. Initially, extraction was performed to obtain starch from sweet potato peels. Subsequently, the bioplastic production process was carried out using the wet mixing followed by the casting method by mixing 5 grams of sweet potato starch with the CMC in various weights (0.1, 0.2, 0.3, 0.4, and 0.5 grams) and gum Arabic (1, 1.5, 2, 2.5, and 3 grams). Mechanical property tests were conducted to evaluate the quality of the bioplastics, including tensile strength, elongation, and apparent modulus. The results indicate that higher concentrations of CMC and gum Arabic enhance tensile strength and rigidity, with a maximum tensile strength of 1.51 MPa achieved. However, increasing CMC concentration can reduce elongation properties. The bioplastics exhibited water absorption ranging from 15.3% to 81.3%, while biodegradability tests demonstrated that samples reached degradation levels of up to 93.8% within 28 days. This study demonstrates that sweet potato peel starch, combined with CMC and gum Arabic, can produce bioplastics with favorable mechanical properties and environmental friendliness, thus presenting a potential alternative method for reducing plastic pollution in Indonesia.

Keywords: bioplastic; carboxymethyl cellulose; gum Arabic; sweet potato peel

1 Introduction

Indonesia is a developing country with serious issues concerning plastic waste. Indonesia is recognized as one of the major contributors to marine plastic debris globally. According to data from INAPLAS and BPS-Statistic Indonesia, Indonesia produces about 64 million tons of plastic waste annually, of which around 3.2 million tons are annually discharged into the ocean [1]. This involves the poor disposal of a cumulative 10 billion plastic bags annually, adding to serious environmental problems.

Conventional plastics have continuously posed an environmental problem because they degrade slowly and have devastating effects on ecosystems. A previous study explained that plastics could stay intact in landfills for decades and contribute to soil and water pollution [2]. In many other cases, conventional plastic degradation leads to its fragmentation into microplastics, which is even more difficult to handle and may lead to grave harm to marine life and generally to ecosystems [3].

Therefore, there is an urgent need to replace conventional plastics with biodegradable alternatives, such as bioplastics. Unlike conventional plastics, bioplastics are more environmentally friendly because they can be degraded biologically. They are commonly produced from starch and cellulose, with plant starch being one of the most accessible feedstocks. Cellulose-based bioplastics are also renewable and biodegradable. These materials generally decompose through microbial activity, making them a promising option for reducing long-term plastic waste [4]

The starch-based bioplastics, for instance, had excellent film-forming properties and proved their potential in packaging and agricultural applications[5,6]. Many crops, such as cassava, corn, and potato, have the potential to be the raw material for bioplastics due to their abundance, low price, and biodegradability[7,8]. Otherwise, starch-based bioplastics are brittle and usually require plasticizers such as glycerol.

Some studies have utilized waste from agriculture as a feedstock for producing bioplastics. For instance, rapeseed press cake and breadfruit peel waste have been used as raw materials for making biodegradable films. The result concluded that such underutilized resources can be transformed into functional bioplastics [9,10]. Additionally, studies have indicated that incorporating cellulose Nano whiskers derived from agricultural waste can improve the mechanical properties of starch-based bioplastics, making them more competitive with traditional plastics[11] and enhancing their flexibility[12].

Despite the big potential for bioplastics from agricultural waste, many challenges persist. Since the raw materials of bioplastics rely on starches, in most cases, such materials have good degradability, but mechanical strengths and barrier properties against moisture are compromised [8,13]. The addition of such additives as *carboxymethyl cellulose* (CMC) and gum Arabic enhances the mechanical properties of starch-based bioplastics. Research has shown that the addition of CMC improves the tensile strength of bioplastics, hence making them more commercially viable [14]. Furthermore, gum Arabic acts as a filler, improving the structural integrity of the bioplastic by filling the spaces between molecules, which contributes to its overall durability[15].

While the addition of plasticizers like glycerol has improved the flexibility of these materials, further research is needed to enhance their tensile strength and durability[12]. Moreover, current formulations often struggle to meet biodegradability standards under diverse environmental conditions, necessitating further study into how additives such as CMC and gum-arabic can be optimized for better performance[14].

Another gap in the existing literature is related to a scarcity of research evidence on the application of sweet potato peel starch in bioplastic products. Sweet potato is one of the most available resources in Indonesia; however, most research tends toward other sources of starch, such as corn and potato, and not much attention is paid to sweet potato as a raw material[4]. Additionally, few studies have investigated the use of acetic acid as a homogenizing agent in the production process, even though it has shown promise in improving the uniformity of bioplastic films[16].

The objective of this study is to develop bioplastics based on sweet potato peel starch, *carboxymethyl cellulose* (CMC), gum Arabic, and glycerol as a plasticizer. This study focuses on the valorization of sweet potato peel waste as an alternative starch source and investigates the effect of varying CMC and gum Arabic compositions on the mechanical properties, water absorption behavior, and biodegradability of the resulting bioplastic films. The bioplastics were prepared using the solution casting method, followed by mechanical and biodegradability characterization. The findings are expected to contribute to the development of environmentally friendly bioplastics from agricultural waste materials.

2 Material and Methods

2.1 Materials

The materials used include sweet potato peel waste sourced from the *Bakpau Telo* industry in Malang City, Indonesia. Carboxymethyl cellulose (CMC) food grade with purity 99%, gum arabic, distilled water, acetic acid (PA), and glycerol (PA) with purity 99,5% were obtained from a chemical store in Surabaya, Indonesia. The equipment utilized for the mixing and stirring process, employing the melt intercalation method, includes a hot plate magnetic stirrer for heating and agitation, magnetic capsules, beaker glass, thermocouples, and beaker glass covers.

2.2 Experimental Setup

2.2.1 Starch Extraction from Sweet Potato Peels

Extraction of starch was conducted to separate starch from sweet potato peel waste. The sweet potato peels were washed thoroughly and then blended with a ratio of 1 kg of peel and 2 litres of water until a smooth mixture was obtained. It is followed by filtration using a filter cloth to separate the starch suspension from the pulp. Other filtration, by the addition of 1 L of water to get more starch, yielded a suspension containing starch and pulp. Mix both suspensions and allow them to stand for 24 hours to obtain a maximum

amount of starch precipitate. The supernatant liquid is discarded, leaving wet starch. The sample was finally dried in a hot air oven at 50°C for 8 h. The starch was then ground using a mortar and pestle until fine and subsequently sieved through a 100-mesh sieve to get uniformly sized particles.

2.2.2 Bioplastic Production

Table 1 shows the composition of bioplastics film formulations. The primary materials, sweet potato peel starch powder and carboxymethyl cellulose (CMC) were weighed according to the specified conditions. Sweet potato starch weighs 5 gram for every sample, while the CMC was varied from 0.1; 0.2; 0.3; 0.4; and 0.5 grams. Gum Arabic with various weigh 1; 1.5; 2; 2.5 and 3 were dissolved in distilled water (aquadest) at 80 °C on a hotplate stirrer. The extracted sweet potato starch and CMC mixture were prepared separately and then combined with the gum Arabic solution using wet mixing. While stirring, 5%wt of 2% acetic acid solution was added until the mixture thickened. Stirring continued for 40 minutes with a spatula at 80°C on the hotplate stirrer. Once the mixture thickened, glycerol (1.5%wt) was added along with the gum arabic solution, and the mixture was stirred until homogeneous. The composition of sweet potato peel starch, CMC, and gum Arabic was adjusted as per the specified conditions. The mixture was poured into petri dish moulds, levelled with a glass plate, and dried in an oven at 70°C. The samples were then removed from the moulds and further air-dried for 5-7 days. A full factorial formulation design was applied, in which five levels of CMC (0.1-0.5 g) were combined with five levels of gum arabic (1-3 g), resulting in 25 bioplastic formulations. The bioplastic samples were analyzed for physical properties (water absorption, biodegradability) and mechanical properties, including tensile strength, elastic modulus, and elongation at break.

Table 1. Composition of bioplastic film formulations

Sample Code	Sweet Potato Peel Starch (g)	CMC (g)	Gum Arabic (g)	Glycerol (wt%)	Acetic Acid 2%	Distilled Water (g)
S1	5.0	0.1	1.0	1.5	5 wt%	2
S2	5.0	0.1	1.5	1.5	5 wt%	3
S3	5.0	0.1	2.0	1.5	5 wt%	4
S4	5.0	0.1	2.5	1.5	5 wt%	5
S5	5.0	0.1	3.0	1.5	5 wt%	6
S6	5.0	0.2	1.0	1.5	5 wt%	2
S7	5.0	0.2	1.5	1.5	5 wt%	3
S8	5.0	0.2	2.0	1.5	5 wt%	4
S9	5.0	0.2	2.5	1.5	5 wt%	5
S10	5.0	0.2	3.0	1.5	5 wt%	6
S11	5.0	0.3	1.0	1.5	5 wt%	2
S12	5.0	0.3	1.5	1.5	5 wt%	3
S13	5.0	0.3	2.0	1.5	5 wt%	4
S14	5.0	0.3	2.5	1.5	5 wt%	5
S15	5.0	0.3	3.0	1.5	5 wt%	6
S16	5.0	0.4	1.0	1.5	5 wt%	2
S17	5.0	0.4	1.5	1.5	5 wt%	3
S18	5.0	0.4	2.0	1.5	5 wt%	4
S19	5.0	0.4	2.5	1.5	5 wt%	5
S20	5.0	0.4	3.0	1.5	5 wt%	6
S21	5.0	0.5	1.0	1.5	5 wt%	2
S22	5.0	0.5	1.5	1.5	5 wt%	3
S23	5.0	0.5	2.0	1.5	5 wt%	4
S24	5.0	0.5	2.5	1.5	5 wt%	5
S25	5.0	0.5	3.0	1.5	5 wt%	6

2.2.3 Tensile Strength Analysis

Before testing, the samples were conditioned in a room with standard temperature and relative humidity (23±2 °C, 52%) for 24 hours. The samples were cut into dimensions of 1 x 6 cm for analysis. Tensile testing was carried out using a universal testing machine under controlled conditions. Tensile strength, elongation at break, and Apparent's modulus were calculated from the obtained stress–strain data to evaluate the mechanical performance of the bioplastic films.. The tensile strength was calculated using Eq. 1.

$$\text{Tensile Strength (kg/cm}^2\text{)} = \sigma = \frac{\text{Tensile Force (F)}}{\text{surface area (A)}}$$

(Equation 1)

2.2.4 Elongation Analysis

The elongation analysis (ε) was performed in the same manner as the tensile strength test. Elongation was expressed as a percentage using Eq. 2:

$$\varepsilon = \frac{\text{Elongation after stretching } (\Delta l)}{Initial\ length\ (lo)}$$

(Equation 2)

2.2.5 Apparent's Modulus Analysis

The modulus values reported in this study represent the apparent modulus calculated from the ratio between tensile strength and elongation at break., as represented by Eq. 3.

$$\text{Apparent's Modulus} = E = \frac{\sigma}{\varepsilon} \quad \text{(Equation 3)}$$

2.2.6 Swelling Analysis

For the water absorption test, the bioplastic was cut into 5 cm x 5 cm pieces and weighed on an analytical balance to determine its initial weight. The bioplastic samples were then immersed in 500 ml of distilled water at room temperature in a 1000 ml beaker for 10 minutes. After immersion, the bioplastic samples were removed and weighed again to determine the final mass. Water absorption was calculated using Eq. 4.

$$\text{Water Absorption (\%)} = \frac{W - W_o}{W_o}\ x\ 100$$

(Equation 4)

Where:

W = final weight of the sample

W_o = initial weight of the sample

2.2.7 Biodegradability Test

After the mechanical properties were analyzed, the biodegradability of the samples was tested by burying them in soil at a depth of 5 cm for 28 days, with observations made every 7 days. Before burial, the samples were weighed and measured. After the test period, the samples were reweighed using an analytical balance. This procedure was repeated for all samples. The percentage of weight loss due to biodegradation was calculated using Eq. 4.

$$\%\text{weight loss} = \frac{W_1 - W_2}{W_1}\ \text{x } 100\%$$

(Equation 4)

Where:

W_1= weight of the plastic before biodegradation testing

W_2 = weight of the plastic after biodegradation testing

3 Result and Discussion

3.1 Appearance

The bioplastic produced in this study exhibited a translucent white colour and was formed into sheets with a width of 100 mm and a thickness of 0.14 mm. The appearance of the product is shown in **Fig. 1**.

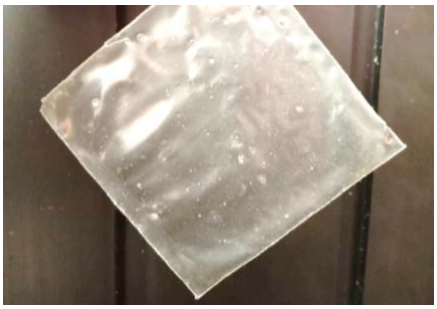


Figure 1. The appearance of bioplastic from sweet potato peel.

The transparency of the bioplastic suggests a uniform dispersion of the materials used in its production, indicating the successful integration of the components. This characteristic is essential for applications where visual clarity and uniformity are desired, such as packaging or biomedical uses. The colour of bioplastics can thus be influenced by the raw material used for its production. The starch-based bioplastics generally have a natural off-white to yellowish colour,

which can be modified by including natural colourants or plant-based pigments[17]. Another critical aspect of appearance is the aspect of transparency of the bioplastic, especially when it is applied in packaging foodstuffs where the visibility of the product is desirable. In general, starch bioplastics are less transparent than conventional plastics based on petroleum, which greatly limits their range of applications[18]

3.2 Mechanical Properties: Tensile Strength

The tensile strength of bioplastic with the various compositions of Carboxymethyl Cellulose (CMC) and gum arabic is shown in **Fig. 2.**

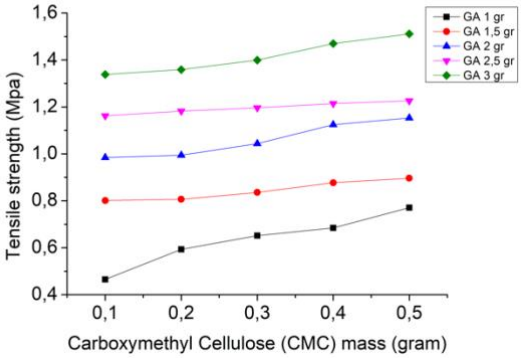


Figure 2 The tensile strength properties of bioplastic in various additional weights of CMC and gum arabic.

Fig. 2 shows that the tensile strength increases proportionally with the addition of Gum Arabic and CMC. The data indicate that the lowest tensile strength, at 0.4648 MPa (or 4.74 KgF/cm^2), was observed in the bioplastic composed of Starch: CMC: Gum Arabic in a weight ratio of 5: 0.1: 1. Conversely, the highest tensile strength, at 1.51 MPa (or 15.41 KgF/cm^2), was recorded for the composition of Starch: CMC: Gum Arabic at 5: 0.5: 3 grams.

The increase in tensile strength and apparent modulus with increasing CMC and gum arabic content may be associated with stronger intermolecular interactions within the starch-based polymer matrix. The hydroxyl and carboxyl functional groups present in CMC, together with the polysaccharide structure of gum arabic, can promote hydrogen bonding interactions with starch molecules, resulting in a more cohesive and compact polymer network. This improved matrix structure may enhance stress distribution during tensile loading and reduce structural defects within the bioplastic films. However, stronger intermolecular interactions can also restrict polymer-chain mobility, leading to lower elongation at break and increased brittleness of the films. The result obtained in this study meets the standards set by the Japanese Industrial Standard (JIS 2-1707), in which the minimum requirement of tensile strength is 0.39 MPa (or 4 KgF/cm^2) for bioplastic materials.

3.3 Elongation Characteristics

The result of the elongation properties of bioplastic with various concentrations of Carboxymethyl Cellulose (CMC) and gum arabic is shown in **Fig. 3**.

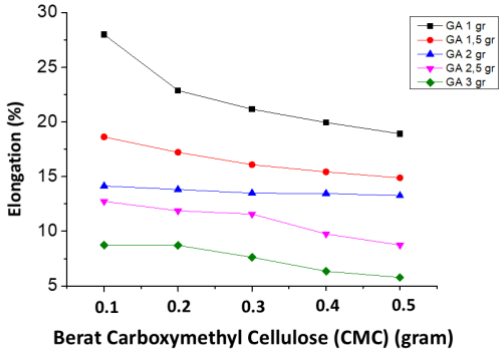


Figure 3 The elongation properties of bioplastic in various additional weights of CMC and gum arabic.

Fig. 3 reveals that the elongation percentage decreases with increasing concentrations of CMC and Gum Arabic. The highest elongation percentage observed was 27.98% for the bioplastic composed of Starch: CMC: Gum Arabic in a ratio of 5: 0.1: 1 gram. The lowest elongation, at 5.78%, occurred in the composition of 5: 0.5: 3 grams of the same components. While the tensile strength of bioplastics increases with the increment of CMC content, their elongation percentage decreases, showing an inverse relation between tensile strength and percentage elongation. This justifies that a material while gaining strength, loses its flexible character. The rise in the CMC content leads to increased viscosity in the CMC solution, which in turn restricts the flow of the polymer chains, hence decreasing the stretching capability of the material before breaking

This effect is compounded by the matrix's non-optimal conditions for binding starch and CMC, leading to the formation of pores and a decreased viscoelastic response. As a result, bioplastics become stiffer, harder, and less elastic. However, Gum Arabic is essential for enhancing elasticity as it facilitates the formation of polymer chain interactions that increase viscoelastic speed and chain mobility, as highlighted by research from [19].

Studies have noted that optimal concentrations of CMC enhance mechanical properties, such as tensile strength and elongation, due to the effective interaction of polymer chains forming a cohesive matrix [20,21]. However, excessive concentrations of CMC lead to a decrease in elongation at break, resulting in more brittle and less ductile materials [22]. This nuanced relationship underscores the importance of balancing CMC concentration to achieve desired mechanical properties in bioplastics. The previous studies show that Scanning electron microscopy (SEM) results have revealed that the distribution and dispersion of CMC within the polymer matrix can significantly affect the elongation properties. A well-dispersed CMC phase can enhance the load transfer between the polymer chains, leading to improved tensile strength and elongation at break [23–25].

3.4 Apparent Modulus Analysis

Apparent Modulus analysis result of the bioplastic product with various compositions of CMC and gum arabic is shown in **Fig. 4**. The result in **Fig. 4** shows an increase in Apparent's modulus with increased concentration of CMC and Gum Arabic, which affect material stiffness. The bioplastic formulation containing the highest amount of these components (5: 0.5: 3 grams of Starch: CMC: Gum Arabic) demonstrated the highest Apparent's modulus, at 26.12 MPa. In contrast, the lowest stiffness, at 1.66 MPa, was observed in the composition with the least amount of these additives (5: 0.1: 1 gram).

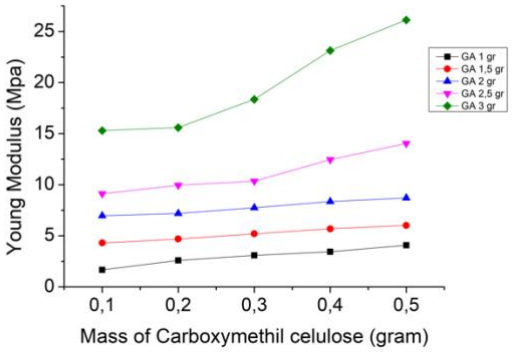


Figure 4 Apparent Modulus properties of bioplastic in various additional weights of CMC and gum arabic

Higher concentrations of CMC typically lead to increased viscosity, enhancing the formation of a cohesive network within the bioplastic matrix. This network is characterized by strong hydrogen bonding interactions among the polymer chains, resulting in improved tensile strength and Apparent's modulus [26,27]. Studies have shown that bioplastics containing CMC at concentrations of 2% to 5% exhibit significantly higher Apparent's modulus values compared to those with lower concentrations, indicating enhanced stiffness and structural integrity[27]. The interplay between CMC and gum arabic concentrations is essential for achieving the desired mechanical properties in bioplastics. In line with this result, a previous study demonstrated that a blend of 3% CMC and 2% gum arabic resulted in a bioplastic with Apparent's modulus significantly higher than that of bioplastics formulated with either polymer alone [26]. This enhancement is attributed to the synergistic effects of the two polymers, where the presence of gum arabic helps to improve the flexibility of the bioplastic while maintaining its stiffness through the reinforcing effects of CMC.

3.5 Analysis of Swelling Properties

The relationship between the composition of Carboxymethyl Cellulose (CMC) and the swelling percentage of bioplastics is presented in Figure **5**.

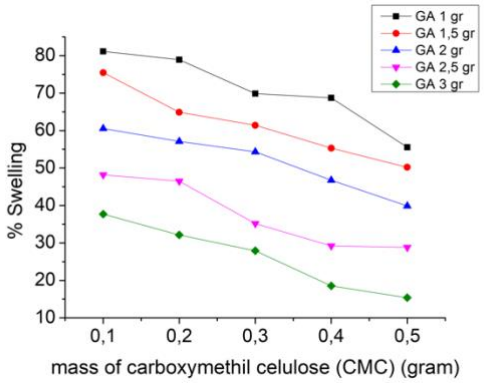


Figure 5 The swelling properties of bioplastic with various weights of additional CMC and gum arabic

The results indicate that increasing the CMC composition reduced the swelling percentage of bioplastic films. A Similar trend was observed with increasing Gum Arabic content. Although starch, CMC, gum arabic, and glycerol are hydrophilic materials, the decrease in water absorption may be associated with improved intermolecular interactions and enhanced hydrogen bonding within the polymer matrix. The addition of CMC and gum arabic likely contributed to a denser and more compact film structure, reducing free volume and limiting water diffusion into the bioplastic network. Consequently, the bioplastic with a starch:CMC:gum arabic composition of 5:0.5:3 showed the lowest swelling percentage (15.3%), while the composition of 5:0.1:1 exhibited the highest swelling percentage (81.3%).

The swelling test helps determine the formation and organization of bonds within the polymer, measured through the percentage increase in polymer weight after swelling[28]. The diffusion of solvent molecules into the polymer results in a swollen gel-like structure. The water resistance of bioplastics is assessed through the swelling test, indicating the percentage of film expansion due to water presence [28]. In this study, Bioplastics products exhibit low water resistance, mainly because these biodegradable materials primarily use starch, a substance with numerous hydroxyl groups that readily absorb water [29]. Compositions with unsubstituted hydroxyl groups are particularly sensitive to water due to the hydrophilic nature of these groups. Additionally, non-homogeneity during mixing can lead to weak bonding among the bioplastic particles, allowing oxygen molecules to penetrate and form cavities within the material.

Optimal compositions of Gum Arabic enhance the bioplastic's structure, as Gum Arabic acts to bind molecules together and fill spaces during the mixing process, thus reducing water absorption[16]. The increase in Gum Arabic composition leads to decreased water absorption, improving the material's overall performance. This research aligns with the standards for conventional eco-green plastics as per SNI 7188.7:2016, which stipulates a water absorption capacity of 21.5% at a soaking temperature of 25°C. The tested bioplastics compositions of Starch: CMC: Gum Arabic (5: 0.4: 3 grams) and (5: 0.5: 3 grams) demonstrated water absorption rates of 18.54% and 15.38%, respectively, meeting these requirements and showcasing their potential as sustainable alternatives to traditional plastics.

3.6 Biodegradability Analysis

The relationship between the composition of Carboxymethyl Cellulose (CMC) and the biodegradation percentage of bioplastics is depicted in **Fig. 6.**

The results depicted in **Fig. 6** illustrate the relationship between the Carboxymethyl Cellulose (CMC) composition in bioplastics and their biodegradation rates. The experiments conducted over one month demonstrate that bioplastics with a composition of 5 grams of starch, 0.2 to 0.4 grams of CMC, and 1 to 1.5 grams of Gum Arabic exhibit high biodegradation rates of up to 93.8%. Notably, a higher content of CMC consistently correlates with decreased biodegradation rates, illustrating an inverse relationship between CMC concentration and biodegradability. This study's findings resonate with existing literature, which posits that the biodegradability of bioplastics is significantly influenced by their chemical composition [30,31]. For instance, research indicates that starch-based materials generally exhibit variable degradation rates depending on the presence of additives like plasticizers[32]. The observed trend in our study, where increased CMC and Gum Arabic content correlates with reduced biodegradability, underscores the complexity of bioplastic matrices and their microbial accessibility, aligning with insights from [33] on the impact of crosslinking in bioplastics.

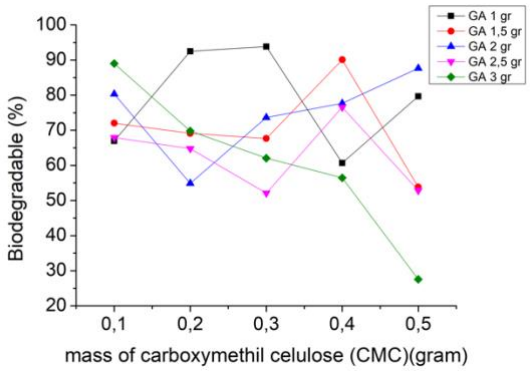


Figure 6 The Biodegradability of bioplastic in various weights of CMC and gum arabic

4 Conclusion

This work successfully prepared bioplastics from sweet potato peel starch, CMC, and gum Arabic for possible application as biodegradable plastics. The mechanical properties, such as tensile strength, Young's modulus, and elongation, were significantly improved by the addition of CMC and gum Arabic, hence justifying the reinforcement capability for enhanced overall durability and strength of these bioplastics. The best formulation had 5.5:0.5:3 grams of starch, CMC, and gum Arabic, respectively, which had the highest tensile strength and stiffness; on the other hand, a higher CMC content reduces the biodegradability of the material. However, the achieved biodegradation rate was as 93.8%, showing potential for further development.

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