

# KINETICS OF BIODEGRADATION OF CASSAVA STARCH - COFFEE GROUNDS BIOPLASTICS IN SOIL AND AQUEOUS MEDIA

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**Abstract.** Starch-based bioplastics have emerged as sustainable substitutes as a result of the buildup of plastic waste. However, high costs and technical flaws frequently restrict their industrial application. While previous studies have explored agricultural fillers, there is a scarcity of kinetic modeling that evaluates biocomposite degradation across diverse disposal scenarios. The purpose of this work is to examine the biodegradation kinetics of bioplastics made from cassava starch and reinforced with spent coffee grounds (SCG) at different concentrations (0%, 10%, 20%, and 30%). Over the course of 28 days, biodegradation tests were carried out in three different settings: acidic solution, tap water, and soil burial. The findings demonstrated that adding SCG greatly sped up the degradation process, with weight loss peaking at 55.3% in soil burial for the 30% SCG formulation. The degradation rate constant ( $k$ ) gradually rose with increasing SCG content in all media, according to kinetic analysis based on a first-order model. Microbial enzymatic activity in soil produced the highest ( $k$ ) value, which was 0.0283 days<sup>-1</sup>. Acidic solution also promoted faster degradation (0.0253 days<sup>-1</sup>) through acid-catalyzed hydrolysis than tap water (0.0189 days<sup>-1</sup>). These findings provide a clear practical guide for the packaging industry to control how fast a product breaks down by simply adjusting the coffee waste content. This research offers a realistic way for businesses to recycle coffee waste into functional packaging that disappears safely after use, supporting a cleaner environment.

*Keywords : Biodegradation, Bioplastics, Coffee, Green Materials, Kinetics*

## 1. INTRODUCTION

Indonesia's plastic waste crisis has reached a critical stage, with estimates indicating a 30% increase in the flow of plastic debris between 2017 and 2025 [1]. The development of biodegradable polymers has become a crucial strategy in the fight against this environmental danger, offering a sustainable substitute for traditional plastics derived from petroleum. Despite being essential for packaging, adoption is frequently impeded by high material costs that outweigh the advantages for the environment. In order to balance sustainability with the "waste-to-wealth" concept, using cassava by-products like peels shows great promise as an inexpensive source that can address technical limitations like sensitivity to moisture and retrogradation processes [2]. According to Darni and Utami [3], these starch-based materials are made to decompose organically without encountering the usual problems with structural integrity. Furthermore, these bioplastics exhibit high ecological safety; research indicates they are non-toxic to the soil upon degradation and can even actively promote the growth of tested plant species [4].

Because it can be recycled and processed in a variety of ways, starch is a great option for the production of bioplastics, which can help cut pollution by providing a sustainable substitute for plastics made from fossil fuels. Its film characteristics are determined by the amylose-to-amylopectin ratio, with higher amylose levels providing greater stiffness and strength [5]. Cassava starch is very popular in Indonesia because it is inexpensive and has good film-forming properties. Research shows that tapioca-based biopolymers frequently produce the best, smoothest, and most flexible results when compared to other starch types [6]. However, its natural brittleness and propensity to absorb moisture frequently restrict its industrial use in architectural and food packaging applications [7, 8]

Beyond technical performance, economic considerations usually take precedence over environmental concerns among consumers. Thus, employing cassava by-products in a "waste-to-wealth" strategy offers a methodical way to produce materials at a reasonable price while tackling issues like retrogradation. It has been shown that incorporating natural fibers and nanoparticles enhances mechanical stiffness and water barrier properties while also accelerating the soil's biodegradation process in order to get around these limitations. [9]. The goal of this engineering and design collaboration is to identify the best material components for a more environmentally friendly future so that these sustainable substitutes can rival traditional synthesized polymers. [6, 7].

Organic fillers have drawn a lot of interest as a cutting-edge waste management technique to enhance the quality of bioplastics. The growing popularity of coffee culture in Indonesia, particularly in places like Bali, has resulted in a significant waste product known as spent coffee grounds (SCG) [10]. Apart from SCG, other waste materials such as coffee flour, mucilage, husk, and silverskin possess tremendous potential for the production of environmentally friendly containers through various methods such as laboratory-scale solvent casting and large-scale extrusion [11]. The use of these agricultural waste materials for the production of additives is extremely beneficial for the creation of a circular economy and industrial symbiosis, which is environmentally friendly and results in a lower carbon footprint compared to other fillers such as commercial metal oxide fillers [12, 13]. While further increasing the filler concentration tends to diminish mechanical properties, it also speeds up the rate of degradation [14].

SCG offers polyphenols and lignocellulosic components that can strengthen the starch matrix chemically [15]. Prior research has shown that adding fillers made from coffee waste can significantly increase flexibility, with increases in elongation at break of up to 106% at low loading levels (1–5% weight percentage); however, this is frequently accompanied by a decrease in Young's modulus and maximum tensile stress [16]. Despite these advantages, the mechanical and barrier properties of bioplastics remain major hurdles to their commercial realization in food packaging [17]. The material's stiffness may be negatively impacted by excessive loading, even though these fillers significantly change the active and physical characteristics needed for protective purposes. In order to improve composite performance and guarantee scalable, affordable, and sustainable industrial applications, waste fillers must be modified or pre-treated to maximize interfacial adhesion [11, 12, 18].

The effects of these composites on the environment during disposal are still a major worry, even with advancements in mechanical reinforcement. The composition of the polymer, environmental factors like temperature, pH, and ultraviolet (UV) radiation, as well as the presence of chemical additives, all interact intricately to drive biodegradation rates [19]. Understanding these factors is paramount because when a polymeric product is released into the environment, it undergoes degradation that may lead to the formation of microplastics if the process is not fully completed [20]. Starch-based bioplastics have shown notable degradation, achieving up to 74% weight loss within 120 days, while also changing soil bacterial dynamics, in contrast to traditional plastics like oxo-LDPE, which may exhibit only a slight weight reduction [21]. Changes in the soil microbial community are brought about by this degradation process, particularly an increase in the number of bacteria that can use plastic materials and those that participate in nitrogen cycling, which appear at particular points during the burial period [21]. It is essential to investigate biodegradation kinetics in order to predict the duration of full assimilation and ensure that no toxic residues remain. Thus far, there has been limited focus on kinetic modeling of SCG-reinforced bioplastics under various real-world environmental conditions.

This study aims to investigate the biodegradation kinetics of bioplastics derived from coffee grounds and cassava starch over a 28-day observation period. The study specifically examines degradation rate constants in three distinct environments in order to model different disposal scenarios. By monitoring weight loss intervals, this study aims to clarify how SCG concentrations affect the environmental lifespan and decomposition efficiency of these sustainable packaging materials.

## 2. METHODS

The traditional markets in Bali, Indonesia, provided the cassava starch used in this study, ensuring the use of a readily available, renewable raw material representative of local resources. To increase the sustainability of the bioplastic production process and utilize post-consumer organic waste, SCG, a natural filler, was collected from local coffee shops. Upon collection, the SCG were first washed thoroughly with distilled water to remove residual sugars, oils, and soluble impurities that could interfere with film formation or biodegradation behavior. The cleaned SCG were then oven-dried at a controlled temperature of 60 °C for 24 hours to eliminate moisture content while preventing thermal degradation of the lignocellulosic components. After drying, the SCG were mechanically sieved to obtain a uniform particle size of 250 µm, which was selected to promote homogeneous dispersion within the starch matrix and improve interfacial interaction.

Solution casting was used to create bioplastic films. After being dissolved in distilled water for about fifteen minutes to reach the proper consistency, 30% glycerol was used to plasticize the cassava starch. The mixture was heated (70–80°C) under stirring until gelatinization occurred. Subsequently, SCG was added at various concentrations (0%, 10%, 20%, and 30% wt%). The homogeneous solution was cast into molds and dried at room

temperature for 48 hours. The resulting films were cut into 4 x 4 cm specimens. Degradation behavior was evaluated in three media: soil, water, and acidic solution. For soil burial, samples were buried at a depth of 5 cm in garden soil with a pH of 6.7 and a moisture content of 32%. For tap water and acidic tests, films were fully immersed, with media replaced weekly to ensure consistency. To create the acidic solution, concentrated acetic acid was diluted with distilled water until a pH of 4.0 was reached, simulating an acidic environment. Every experiment was carried out at room temperature.

The samples from every environment were meticulously extracted at pre-established intervals of 3, 7, 14, and 28 days. Before being analyzed, the recovered samples were allowed to air-dry at room temperature for a full day after being gently rinsed with distilled water to get rid of any surface residues or adhered soil particles. The dried samples were then weighed using an analytical balance to determine weight loss as an indicator of biodegradation progress. The weight loss percentage was calculated using the equation:

$$WL = \frac{W_0 - W_t}{W_0} \times 100\%$$

where  $W_0$  is the initial weight and  $W_t$  is the weight after the specified degradation period.

### 3. RESULTS AND DISCUSSION

#### 3.1 Results

The visual appearance of the bioplastic films is significantly impacted by the concentration of SCG, as shown in Figure 1. The film's ability to retain high transparency and a smooth, homogeneous surface at 10% loading indicates excellent compatibility and uniform filler dispersion within the starch matrix. Higher opacity and a darker hue are the results of increasing the SCG content to 20%. At this stage, localized agglomeration and minor surface irregularities start to show, indicating that the matrix is starting to reach its limit for consistent filler integration. The film becomes primarily opaque and visually heterogeneous at the maximum loading of 30%. There is noticeable particle clustering, which results in structural discontinuities and a rougher texture.



Figure 1. Visual appearance of cassava starch-based bioplastic films reinforced with varying concentrations of spent coffee grounds (SCG): (left) B1 with 10% wt, (center) B2 with 20% wt, and (right) B3 with 30% wt.

Over the course of 28 days, the biodegradation of bioplastics made from cassava starch and coffee grounds was assessed in three different media: soil, acidic solution, and water. The percentage of weight loss for each formulation (0%, 10%, 20%, and 30%) was monitored at intervals of 3, 7, 14, and 28 days to determine the degradation profile. The comprehensive results of the weight loss measurements are summarized in Table 1, while the visual progression of the degradation is illustrated in Figure 2.

Table 1. Percentage of weight loss of bioplastic samples in various degradation media over 28 days.

Degradation Medium	Sample Code	SCG Content (%)	3 Days (%)	7 Days (%)	14 Days (%)	28 Days (%)
Tap Water	B0	0	4.2	9.3	13.1	21.3
	B1	10	7.4	14.2	19.2	33.2
	B2	20	7.7	16.1	22.4	38.8
	B3	30	7.2	15.4	23.4	36.5
Acidic solution	B0	0	8.4	17.2	24.1	40.1
	B1	10	8.8	18.3	25.5	42.3
	B2	20	8.9	18.5	25.8	42.4
	B3	30	9.2	20.1	27.7	49.5
Soil Burial	B0	0	10.2	21.8	29.2	50.4
	B1	10	9.3	21.7	28.4	44.9
	B2	20	10.5	22.6	32.4	51.9
	B3	30	10.9	22.9	36.8	55.3

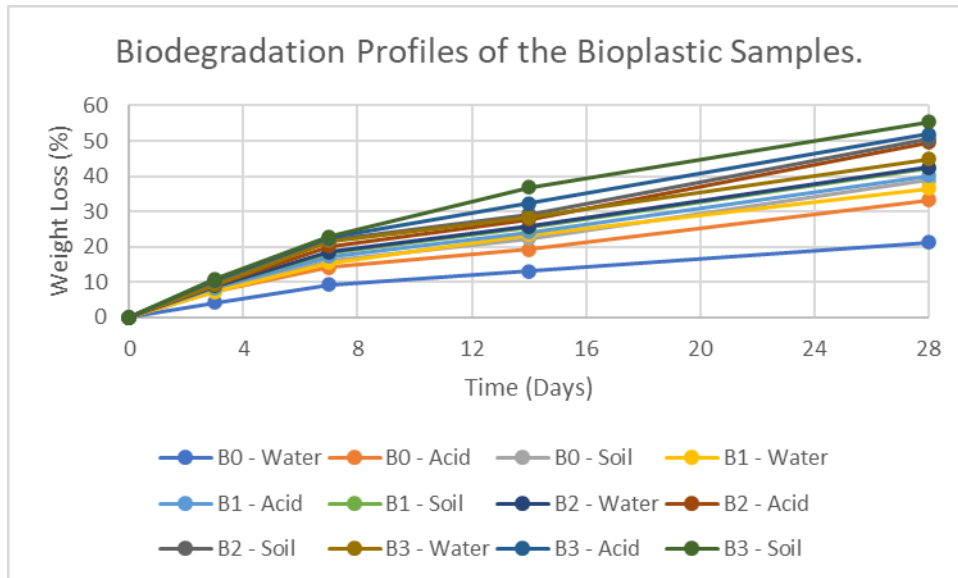


Figure 2. Biodegradation profiles of bioplastic samples in various environmental media over 28 days.

Over the course of the 28-day observation period, all bioplastic formulations showed a progressive increase in weight loss, as shown in Figure 2. With a maximum weight loss of 50.4% in soil, the control samples continuously displayed the lowest degradation rates across all media, as shown by the lower trajectories on the graph. On the other hand, the degradation process was considerably accelerated by the addition of SCG. This pattern is evident in Figure 2, where samples with 30% SCG had the greatest weight loss across all environments, peaking at 55.3% in soil at the conclusion of the investigation.

The degradation environment, specifically microbial activity, moisture, and pH, had a major impact on the rate of decomposition. Regardless of SCG concentration, soil burial consistently displayed the highest weight loss values, followed by acidic solution, while tap water displayed the lowest rates. Figure 2 illustrates this hierarchy by demonstrating that, in contrast to the aqueous media, the soil burial curves maintain a steeper incline. For instance, at 20% SCG loading, the weight loss after 28 days was 51.9% in soil, 42.4% in acidic solution, and 38.8% in water. These results, supported by both the tabular and graphical data, indicate that both filler concentration and the nature of the medium are primary determinants of the biodegradation behavior of these biocomposites.

### 3.2 Discussion

#### *Effect of Spent Coffee Grounds (SCG) on Biodegradation*

The findings unequivocally show that adding SCG speeds up the weight loss of bioplastics made from cassava starch. The disruption of the starch matrix's continuity by the SCG particles is the primary cause of this phenomenon. Higher SCG loadings cause more filler agglomeration, which results in micro-voids and interfacial gaps between the filler and the polymer matrix, as the morphological analysis shows. The surface area available for enzymatic and hydrolytic attack is increased by these structural discontinuities, which make it easier for moisture and microbes to enter the inner layers of the film. However, an unexpected trend occurred in tap water, as the 30% SCG sample (B3) degraded slower than the 20% sample (B2). This most likely occurred as a result of the coffee's natural oils repelling water and its denser particles filling the pores more firmly, offering momentary protection in neutral environments. Unlike inorganic reinforcements like bentonite, which tend to stabilize the bioplastic and slow down the degradation rate by increasing material integrity, organic fillers like SCG and coffee skin fibers actively promote decomposition. Previous studies on cassava-based bioplastics reinforced with coffee skin fibers reported significant biodegradation values ranging from 32.9% to 68.9%, underscoring the effectiveness of coffee-derived waste as a natural degradant [22].

Additionally, coffee grounds' hydrophilic lignocellulosic components improve water absorption and serve as a catalyst in the early phases of degradation. Recent research indicates that 10% filler content (B1) provides the best balance by slightly improving mechanical properties while enhancing degradation, whereas higher filler levels (B2 and B3) further increase biodegradability at the expense of tensile strength and flexibility. [14]. This rapid weight loss in soil within 28 days is consistent with observations of starch-based films lacking high-integrity stabilizers, which typically undergo rapid fragmentation after the initial stages of burial [23].

*Comparative Analysis of Degradation Media*

The study's degradation rates were consistently grouped in a hierarchy, with the soil environment having the largest impact, followed by acidic solutions and tap water. In the soil environment, the formulation containing 30% SCG experienced the greatest weight loss, peaking at 55.3%. This rapid decomposition is attributed to the synergistic effect of biotic and abiotic factors; specifically, the diverse community of soil-dwelling bacteria and fungi secretes amylase and other extracellular enzymes that hydrolyze starch polysaccharides into simpler sugars for microbial metabolism. This pattern is consistent with earlier studies on bioplastics based on starch, which reported higher weight loss in soil (up to 63%) compared to aquatic environments such as river water (54%), with significantly higher degradation rate constants observed in soil media [25].

A low pH environment actively promotes the hydrolysis of glycosidic bonds within the starch chain by acid, as evidenced by the higher rate of degradation seen in acidic solution compared to tap water in aqueous environments. This chemical cleavage increases the matrix's solubility and fragmentation susceptibility by reducing the polymer's molecular weight. On the other hand, tap water loses weight the slowest of all the environments tested because it lacks the concentrated microbial activity present in soil as well as the accelerated chemical reactivity of an acidic medium. The kinetic calculations of Syuhada [25] corroborate these findings, confirming that the superior availability of biological degradants in soil usually results in a higher rate of biodegradation than in water-based media.

*Biodegradation Kinetics*

A first-order kinetic model was used to assess the quantitative analysis of the degradation process. Deep insight into how the material composition and the external environment affect the bioplastic's lifespan can be gained from the rate constant ( $k$ ), which shows the rate of weight reduction over time.

Table 2. Calculated first-order degradation rate constants ( $k$ ) for SCG-reinforced bioplastics in different media.

Degradation Medium	Sample Code	SCG Content (%)	Rate Constant ( $k$ ) (days <sup>-1</sup> )
Tap Water	B0	0	0.0082
	B1	10	0.0157
	B2	20	0.0177
	B3	30	0.0189
Acidic solution	B0	0	0.0136
	B1	10	0.0175
	B2	20	0.0236
	B3	30	0.0253
Soil Burial	B0	0	0.0168
	B1	10	0.0188
	B2	20	0.0240
	B3	30	0.0283

The data in Table 2 reveals a significant correlation between the filler concentration and the degradation velocity. In all tested media, the rate constant ( $k$ ) increases progressively as the SCG content rises from 0% to 30%. In tap water, for instance, the  $k$  value nearly doubles from the control (0.0082 days<sup>-1</sup>) to the 10% SCG variation (0.0157 days<sup>-1</sup>). This suggests that adding even a small amount of coffee grounds significantly changes the starch matrix, making it more porous and more likely to absorb moisture. This pattern is in line with research by Amer [24], who found that while pure synthetic polymers stay the same, weight loss and water absorption rise with increasing starch or organic content. The kinetic behavior is also significantly influenced by the surrounding circumstances. The Soil Burial medium consistently had the highest  $k$  values, with the B3 sample reaching its peak at 0.0283 days<sup>-1</sup>. This faster soil decomposition is consistent with research by Syuhada [25], which found that soil weight loss was significantly higher (63%) than in aquatic environments, such as river water (54%), and that this was backed by higher degradation rate constants in soil media. The high rate in soil is caused by microbial enzymatic secretion, especially amylase, which actively breaks down starch chains into glucose units that can be metabolized.

Furthermore, the acidic solution medium yielded higher  $k$  values than tap water. The acidic environment promotes acid-catalyzed hydrolysis of the glycosidic bonds. The results indicate that the B3 sample degraded considerably more quickly in acidic solution (0.0253 days<sup>-1</sup>) than in neutral water (0.0189 days<sup>-1</sup>). This confirms that a lower pH environment provides a chemical "shortcut" for polymer chain scission. However, the design of these bioplastics must consider the specific filler type; as noted by Oblitas [26], while organic fillers generally aid decomposition, certain structural components like cellulose can sometimes slow down the degradation rate compared to pure starch controls.

In summary, this study demonstrates that by merely varying the quantity of coffee grounds added, we can regulate the rate at which the bioplastic decomposes. In plain water, the material is fairly durable, but once it is buried in the ground, it breaks down rapidly. However, this degradability is closely linked to the material's initial mechanical properties. Widantha [14] asserts that the inclusion of SCG affects both flexibility and tensile strength. A moderate filler loading of 10% (B1) was found to reinforce the structure, achieving a peak tensile strength of 2.37 MPa and a slight improvement in elongation to 32%. In contrast, higher filler concentrations (20% and 30%) led to a significant decline in tensile strength (down to 1.18 MPa) and a sharp reduction in ductility (dropping to 14% elongation). As supported by Amer [24] and Oblitas [26], this weakening of the structural matrix at higher SCG loadings not only restricts polymer chain mobility but also creates more entry points for environmental degradation agents. The B3 sample has the highest rate of degradation ( $0.0283 \text{ days}^{-1}$ ) and the lowest mechanical strength, which can be explained by this dual effect. While a high SCG content is best suited for applications requiring quick composting, these results demonstrate that biocomposites are a flexible and sustainable alternative to traditional packaging technologies, emphasizing the need to find a balance for packaging that demands greater mechanical durability.

#### 4. CONCLUSION

This study concludes that the addition of SCG effectively accelerates the biodegradation of cassava starch-based bioplastics, with the rate constant peaking at  $0.0283 \text{ days}^{-1}$  in the 30% SCG formulation buried in soil. The rate of degradation is directly regulated by the concentration of SCG. The material becomes more porous and has a larger surface area when more filler is added, which enables the decomposition speed to be changed as necessary. Even though the soil environment and acidic conditions significantly improve decomposition through enzymatic activity and hydrolysis, a higher filler content results in a trade-off by lowering mechanical durability. These results show that coffee waste can be recycled to create beneficial biocomposites that actively prevent environmental buildup. It is intended that these findings will encourage broader industrial adoption of circular economy principles, ensuring that future packaging products not only serve their intended function but also safely and effectively return to the ecosystem.

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