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Elucidation of Carbon Dioxide Generated Via Biodegradation of Bioplastic Derived from Local Banana Peel

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Much research has recently focused on sustainable substitutes for traditional petroleum-based plastics due to the worldwide environmental crisis and the growing plastic waste problem. Bioplastics have become a possible alternative to lessen the adverse environmental effects of conventional plastics. Thus, conventional plastics are primarily linked to pollution and ecological deterioration throughout their lifecycle, exacerbating environmental problems. This research responds to the necessity to look into sustainable alternatives. This study aims to achieve sustainable development by effectively utilizing banana peel wastes from different stages of ripening to lessen carbon footprints and greenhouse gas emissions. This study used five characterization methods: sensory evaluation test, ATR-FTIR analysis, water solubility, soil burial test, and aerobic biodegradation measurement. Observation recorded that the ripe bioplastic has a sweet scent due to 90% of the total esters in the film. The texture of each film can have a different impact on the water solubility. ATR-FTIR analysis evaluated the functional groups in the films at specific bands, such as C-O and C-H stretching. The results showed that only minimally existing unripe and overripe peaks are at wavenumber 2250-2100 $cm^{-1.}$ A few parameters, including soil moisture, pH, and temperature, were thoroughly assessed as part of a biodegradability study of the bioplastic generated. This research shows that bioplastic from all stages of ripening degrades more quickly in wet soil and at high temperatures. Bioplastics undergo degradation by microorganisms, which generate gases, biomass, and water when buried in soil. Aerobic biodegradation measurement was conducted by titrating KOH and HCI with the presence of phenolphthalein for five consecutive weeks to determine the amount of released CO_2. Among all these tests, only overripe bioplastic exhibits the highest rate of degradation, followed by ripe and unripe.

Keywords: Bioplastics; ATR-FTIR; physicochemical; aerobic biodegradation; microorganisms

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Conventional plastics are widely used and are primarily sourced from fossil fuels that cause serious environmental problems, such as pollution, resource depletion, and ecological deterioration. Current research is to find sustainable alternatives to conventional plastics derived from petroleum due to the growing issue of plastic waste and the global environmental catastrophe. Bioplastics have shown great promise as an alternative since they leave fewer carbon footprints and emit fewer greenhouse gases into the atmosphere than traditional plastics [1–3].

Fruit peel scraps, usually thrown away, comprise between 15% and 60% of the fruit waste generated [4]. Approximately 35% of the total weight of the banana fruit originates from its peels. Consequently, 26 million tonnes of banana peel are produced annually, making it a resource that may be useful in the future [5–7]. The nutritional value of banana peels is widely recognised. A 100 g portion of banana peels provides 18.50 g of carbohydrates, 2.11 g of fat, 0.3 g of protein, 1.60 mg of iron, 715 mg of calcium, 117 mg of phosphorus, 0.12 mg of B vitamins, and 17.50 mg of BC vitamins. The majority of a banana peel's composition is water and carbohydrates. Therefore, carbohydrate in the form of starch is present in banana peels [8]. These carbohydrates are readily converted to organic acids by aerobic digestion, a process frequently employed to examine carbon dioxide production as a sign of the biodegradability of bioplastics. Biodegradable polymers contain a substantial quantity of starch content as a primary material. Glucose levels will rise as banana peels ripen. In any case, overripe peels will convert their starch to glucose, whereas unripe peels become excessively stiff even though they contain much starch. Thus, it is possible to propose banana peels as a viable hotspot for the production of bioplastics [9].

There is a critical need to explore sustainable alternatives that reduce environmental impact while maintaining functionality. This research addresses this need by investigating the viability of using banana peels, an abundant and underutilized waste resource, to produce biodegradable bioplastic films. Additionally, this research will examine how factors such as

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temperature, pH, and moisture content influence the biodegradability of these films and the resulting carbon dioxide (CO_2) emissions during their decomposition. Therefore, it is crucial to investigate the carbon dioxide released during the biodegradation of bioplastics made from local banana peel waste. Biopolymers and bio-based fibres from renewable waste and resources can resolve several environmental issues related to plastic. This research promotes a sustainable and ecologically friendly approach to materials and waste management by improving resource efficiency and providing information for product development and waste management decisions.

EXPERIMENTAL

Chemicals and Materials

Food-grade corn starch powder, a 10% sodium hypochlorite solution (NaOCl), a 25% glycerol solution, and citric acid are among the chemicals employed in this study. Banana peel with different ripening stages (unripe, ripe, and overripe) was the primary raw material used in this study. Peels are crushed into a fine powder using a laboratory-scale grinder (Model: XH-12, Brand: Hong Jin). Country: Malaysia). A particular amount of powdered banana peel was combined with glycerol (used as a plasticiser), citric acid, and corn starch (used as a filler) to produce the bioplastic. The banana peel powder was treated with a 10% sodium hypochlorite solution (NaOCl) before compounding, enhancing the mechanical properties of the bioplastic.

Sample Preparation Methods

Preparation of Banana Peel Powder

Ripe and overripe banana peels collected from a local vendor selling banana fritters in Arau, Perlis. Each sampling collects approximately 1 to 1.5 kg of ripe and overripe banana peels. Additionally, unripe bananas were purchased to collect peels from those fruits. The unripe banana peels were sliced using a stainless steel knife. The peels were immersed in a 100 mL sodium hypochlorite (NaOCl) solution to remove the wax. After this treatment, any excess NaOCl was removed by boiling the peels in 500 mL of distilled water for 30 minutes. The water was then carefully poured off. One gram of citric acid dissolves in 10 millilitres of distilled water, and the peels are subsequently immersed in this solution. The optimal dried peels were obtained in an oven for 24 hours at 60 °C. The ripe and overripe banana peels underwent the same steps repeatedly. After drying, the peels were ground using a laboratory-scale grinder and sieved through a 60-mesh sieve to produce fine banana peel powder. The powdered banana peels were kept in airtight plastic packages at room temperature.

Preparation of Bioplastic Films

In a 500 mL beaker, mix 100 mL of corn starch solution, 3 g of glycerol to act as a plasticiser, and 1 g of powder made from unripe banana peels. The corn starch solution should be sticky and completely dissolved in boiling water before adding the powdered banana peels and glycerol to create a homogeneous mixture. This solution was stirred for 50 minutes and maintained at a boiling temperature (~100 °C). After 50 minutes, this sticky solution was placed on the moulds and dried in the oven for 24 hours at 50 °C. The same methodologies were employed for both ripe and overripe banana peels [10].

Characterisation Methods

Sensory Evaluation Test

Unripe, ripe, and overripe banana peel powder was analysed for colour, smell, texture, and appearance. Colour may indicate changes in the production process or the presence of pollutants, while smell may indicate any unpleasant smells that might reduce the utility of the bioplastic. The texture of the films helps in understanding the consistency of the material, while the physical appearance aids in visually comparing the samples and identifying any apparent differences. Subsequently, the powdered banana peel from various ripening stages was converted into a bioplastic film by applying specific chemicals, as detailed in the methods for preparing bioplastic films. This sensory evaluation test effectively analyses each film's smell or fragrance, texture, and visual characteristics. These attributes play a critical role in shaping the overall perception of the final product [11].

Fourier Transform Infrared Spectroscopy (FTIR) Analysis

The functional groups in the bioplastic material can be determined by Fourier Transform Infrared Spectroscopy (FTIR) analysis using a Shimadzu IRAffinity-1S ATR-FTIR Spectrophotometer (Brand: Shimadzu, Country: Japan). This method facilitates comprehension of the bioplastics' chemical composition and the detection of any alterations that occur throughout the biodegradation process [12].

Water Solubility Test

The bioplastic films were meticulously cut with a scalpel to obtain sections with a diameter of about 20 millimetres. All banana peels were dried for one day at 105 °C. Following this step, the films were placed in a desiccator filled with silica gel for 30 minutes. After weighing each film (first dry weight, W_i), it was moved to a beaker and filled with 50 mL of distilled water. The film was kept at room temperature for a full day.

The water was removed. The film underwent drying at 105 °C for a complete day. The film was weighed again to obtain the final, W_f [13]. The percentage of water solubility (%) was determined using Equation (1):

$$S\ (\%) = \frac{W_i - W_f}{W_i} \times 100\% \quad (1)$$

Soil Burial Test

The bioplastics were buried in the soil under regulated conditions to assess their biodegradation. The samples were placed in a container with soil 2 cm deep. Environmental variables such as soil pH, moisture content, and temperature were managed and tracked throughout the research study. In order to assess soil moisture effectively, it is important to measure both dry and wet soil conditions. Meanwhile, there are also two different controlled settings for temperature variables, which are 9 °C and 35 °C. The neutral pH of the soil was also chosen for characterisation methods since it was easy to find neutral soil in our surroundings. Since pH can significantly impact microbial activity and the biodegradation rate, the neutral pH of the soil employed in this investigation is crucial. Additionally, the bioplastics' weight loss was repeatedly observed over a predetermined seven-day period to determine the biodegradation rate. Tracking the weight shift of the bioplastic samples as they decompose in the soil offers a simple means of quantifying deterioration [14].

Aerobic Biodegradation Measurement Test

By ASTM D5988, samples were put through an aerobic biodegradation test in soil to evaluate the biodegradation of the bioplastic sheets. 150 g of soil sieved to a particle size of less than 2 mm was added to a sealed jar with each film sample to ensure uniformity. A beaker with 20 mL of 0.5 M KOH solution was placed inside each jar to absorb the CO_2 produced during biodegradation. After that, the jar lids were securely shut to preserve the test-controlled setting. Weekly assessments were conducted to quantify the volume of CO_2 absorbed by the KOH solution. The KOH solution was titrated with 0.25 N HCl while phenolphthalein was present as an indicator to accomplish this [15,16].

Table 1. Sensory evaluation test of banana peel powder.

Stages of ripening	Colour	Smell	Texture	Physical Appearance
Unripe	Dark Brown	Odourless	Lumpy	
Ripe	Brownish Yellow	Sweet smell	Dry	
Overripe	Brown	Slightly sweet	Slightly dry	

RESULTS AND DISCUSSION

Sensory Evaluation Test

According to **Table 1**, the powder made from unripe banana peels was dark brown. This phenomenon may be due to the high concentration of phenolic compounds in unripe banana peels, which possess antibacterial and antioxidant properties [17]. Additionally, it was found that the unripe powder has no odour. As fruits ripen, the concentration of volatile compounds typically rises. This phenomenon can be attributed to the lower levels of these compounds found in unripe peels. Then, the texture of unripe banana peel powder is lumpy. The higher moisture content may influence the lumps in unripe peels, which can cause agglomeration during the drying and grinding process, necessitating the adjustment of drying procedures and storage settings [18].

The powdered ripe banana peel had a yellowish-brown shade due to the presence of carotenoids like lutein and β-carotene, which may be crucial in giving banana peel powder a slightly yellow colour. The chloroplasts detected in leaves were similar to the carotenoids found in banana peels. The darker yellow colour of the unripe banana peel powder may be due to a combination of factors, including the higher overall carotenoid content in the peel tissue and its distinct carotenoid aggregation patterns [19]. The ripe powder also had a sweet smell. Research by Netshiheni et al. [20] has proven that the sweet smell is due to the presence of esters. More potent aromas are generated when the volatile constituents of an ingredient are int ricately associated with its fragrance profile. [21]. During the ripening process, molecules known as esters are produced. Acetate esters are the most common type, making up about 50% to 80% of all esters [22]. Thus, it also has a dry texture. It implies that the powder was correctly ground.

Table 2. Sensory evaluation test of banana peel film.

Stages of ripening	Smell	Texture	Physical Appearance
Unripe	Slightly foul	Sticky	
Ripe	Sweet	Sticky, brittle	
Overripe	Rancid	Dry, brittle	

Overripe banana peel powder exhibited a brown appearance due to the increase in chlorophyll enzyme activity, which plays a part in the deterioration of chlorophyll and the ensuing browning process [23]. Activating the enzymes polyphenol oxidase and peroxidase causes this enzymatic browning in overripe banana peel powder [24]. Thus, the smell was not as strong as it would have been at the ripe stage, indicating the presence of some volatile molecules. In contrast to the ripe stage, the texture was slightly dry. It shows that even though the overripe peel had lost most of its moisture, it might still have some left.

Table 2 outlines each bioplastic film's sensory evaluation, including each banana ripening stage's smell, texture, and physical appearance. These characteristics are necessary since they significantly impact the final product's quality [11].

According to the smell or fragrance analysis, the unripe bioplastic film had a slightly foul odour. Unripe banana peels may contain volatile substances that cause them to become unstable and release an offensive odour. Through texture analysis, it was determined that the unripe bioplastic film exhibited a sticky texture. Due to their increased moisture content, the unripe banana peel bioplastic films may be stickier than ripe or overripe bioplastic films. When bananas ripen, the amount of starch in their peels reduces. The higher starch content in unripe banana peels may also contribute to the stickiness [25].

There was a sweet smell to the ripe bioplastic film. The film smells much better due to its esters. Acetate and butyrate were the volatiles found in the ripe stage, making up more than 90% of the total esters generated [26]. For texture analysis, it was brittle and sticky. Brittleness is a sign of rigidity and fragility, probably due to compositional alterations. Additionally, starch molecules are utilised as a raw material to make bioplastics brittle due to the crystalline form of amylose. Amylose and amylopectin must be separated from each other in order to produce bioplastics that work better [27].

The overripe film smelled of rancidity. According to Liu et al. [28], there was speculation that the rancid smell could be caused by using specific organic acids in bioplastics. The overripe films had a brittle and dry texture. The starch content affected the texture of the bioplastics, giving them a dry texture. This dryness might reduce the films' flexibility and increase their susceptibility to cracking [29].

ATR-FTIR Analysis

Total attenuated reflectance Fourier transform infrared (ATR-FTIR) analysis was employed to evaluate samples at three distinct stages of banana peel ripening. An average of 32 scans and five repetitions were used to acquire the spectra at a resolution of 4 cm^{-1}, covering the wavenumber range from 4000 to 600 cm^{-1} [16]. **Figure 1** displays the film spectral distributions. According to **Tables 3, 4,** and **5**, the symmetrical stretching vibrations of hydroxyl (O–H) correlate to a moderate absorption band at 3281 cm^{-1} in unripe bioplastic, a mild vibration at 3298.5 cm^{-1} in ripe bioplastic, and also 3261 cm^{-1} in overripe bioplastic. Moreover, the three hydroxyl functional groups might be attributed to the used of glycerol as plasticizers in the films formulation [14]. In addition, it also results from the stretching vibrations of the hydroxyl groups found in phenols, water, carbohydrates, and organic acids [30].

Additionally, a low vibration was observed in the C–H stretching absorption band of the symmetrical hydrocarbons CH, CH_2, and CH_3 at 2941.5 cm^{-1}, 2938.5 cm^{-1}, and 2919 cm^{-1} for the unripe, ripe, and overripe films, respectively. C-H stretching happens in alkanes in the range of 3000 to 2800 cm^{-1}. The wavenumbers of 2155.5 cm^{-1} for unripe films and 2155 cm^{-1} for overripe films indicate the presence of C≡C (alkyne). The increased water absorption exhibited by hydrophilic starch and saccharides is attributed to the O-H stretching vibrations, which correspond to the peaks observed at approximately 1580 cm^{-1} [31].

The spectral data additionally showed peaks at 1399 cm^{-1}, 1406.5 cm^{-1}, and 1401 cm^{-1} for unripe, ripe, and overripe, respectively. The observed peaks resulted from N-H stretching absorptions associated with the primary amine [32–34]. The C–O stretching vibrations of pectin and polysaccharides have been identified as responsible for the spectral bands observed at 1024, 1032.5 cm^{-1}, and 1039 cm^{-1}. The ester bond is associated with peaks between 1000 cm^{-1} and 1300 cm^{-1}.

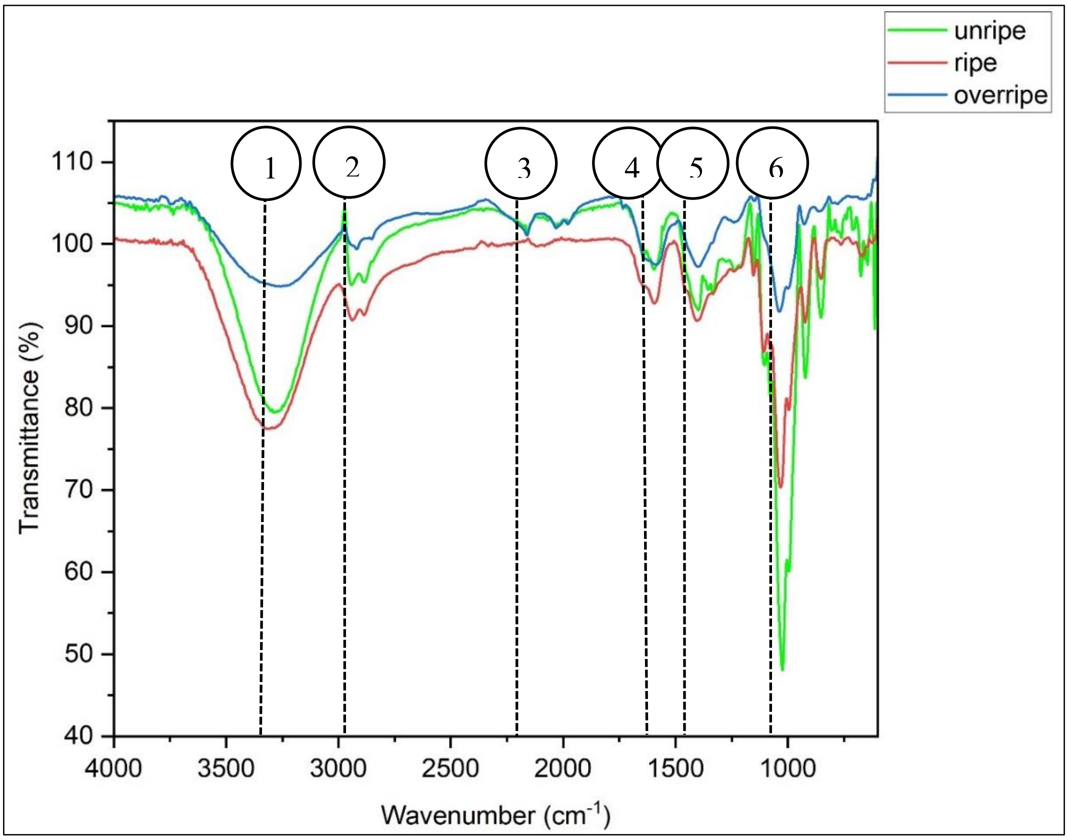

Figure 1. Fourier-Transform Infrared spectroscopy (FTIR) of the films.

Table 3. FTIR spectra of unripe bioplastic.

No.	Functional Group	Wavenumber (cm^{-1})	Spectral Range
1.	O-H (alcohol)	3281	3400-3200
2.	C-H (alkane)	2941.5	3000-2800
3.	C≡C (alkyne)	2155.5	2250-2100
4.	H-O-H	1595	1580
5.	N-H (amine)	1399	1640-1550
6.	C-O (ester)	1024	1300-1000

Table 4. FTIR spectra of ripe bioplastic.

No.	Functional Group	Wavenumber (cm^{-1})	Spectral Range
1.	O-H (alcohol)	3298.5	3400-3200
2.	C-H (alkane)	2938.5	3000-2850
3.	C≡C (alkyne)	-	2250-2100
4.	H-O-H	1595	1580
5.	N-H (amine)	1406.5	1640-1550
6.	C-O (ester)	1032.5	1300-1000

Table 5. FTIR spectra of overripe bioplastic.

No.	Functional Group	Wavenumber (cm^{-1})	Spectral Range
1.	O-H (alcohol)	3261	3400-3200
2.	C-H (alkane)	2919	3000-2850
3.	C≡C (alkyne)	2155	2250-2100
4.	H-O-H	1592	1580
5.	N-H (amine)	1401	1640-1550
6.	C-O (ester)	1039	1300-1000

Table 6. Solubility for bioplastic film.

Stages of ripening	Solubility (%)
Unripe	48.6
Ripe	74.35
Overripe	55.79

Water Solubility Test

Solubility plays a crucial role in films that degrade naturally. In the presence of water, a film's low solubility in water signifies its stability [14]. **Table 6** presents the solubility of the produced film.

As shown in **Figure 2**, the unripened film had the lowest solubility (48.6%), while the ripe film had the highest solubility (74.35%). Low-solubility films might serve as shields to improve the product's integrity and water resistance [35]. Unripe banana peel films had a compressed and rough surface. It will increase the barrier to water penetration and film dissolution due to the hydrophilic behaviour of bioplastics composed of glycerol and starch [36]. As a plasticiser, glycerol enhances bioplastics' flexibility and workability. It is known for its hydrophilic properties, meaning it readily attracts water. In bioplastics, glycerol is a softening agent, increasing the material's affinity for water. This hydrophilic behaviour contributes to the increased solubility of the film. Starch is another hydrophilic component often used in bioplastics. Its molecular structure contains hydroxyl groups that form hydrogen bonds with water molecules. This interaction enhances the film's ability to absorb moisture and dissolve more easily in water. The amount of hydrophilic (water-attracting) compounds in the film may grow as it matures. Meanwhile, for overripe film, it shows 55.79% solubility. The film is still quite soluble, although less than the ripe film.

Figure 2. Water solubility test for unripe bioplastic film.

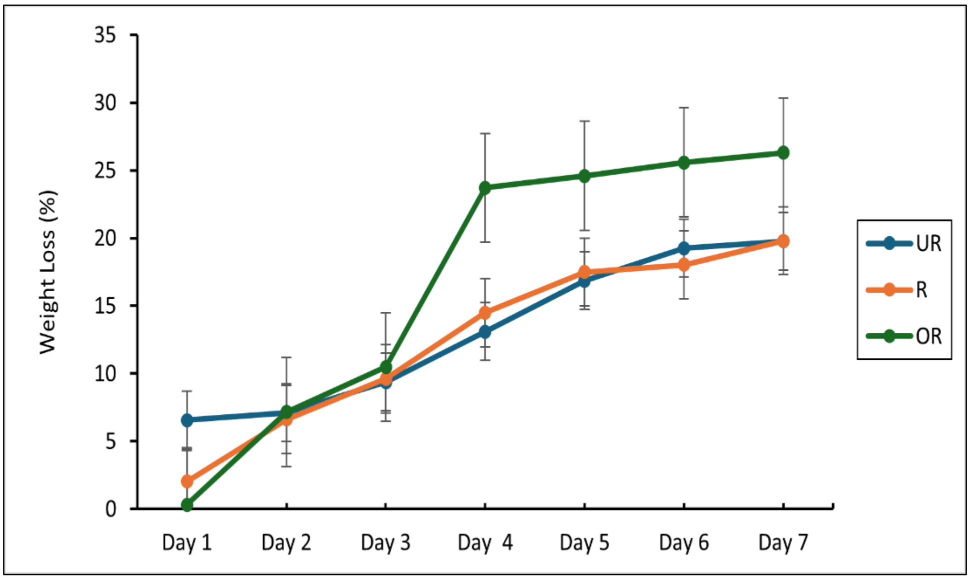

Figure 3. Weight loss of soil burial sample in dry soil.

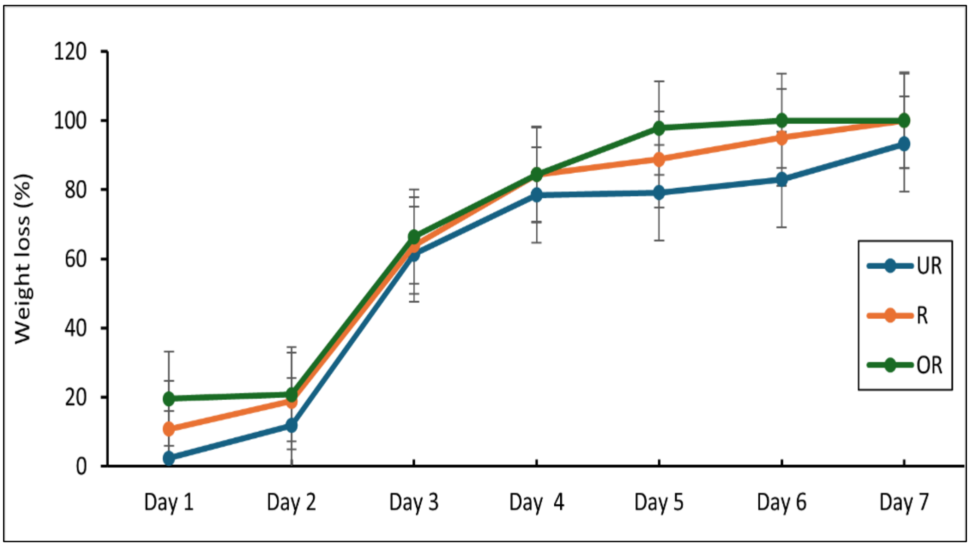

Figure 4. Weight loss of soil burial sample in wet soil.

Effect of Biodegradation on Soil Moisture

Figures 3 and **4** show the outcomes of testing the bioplastic film made from unripe, ripe, and overripe banana peels with different soil moisture levels. Over time, the weight of the samples gradually decreased. Furthermore, it was noted that the sample broke down in the soil within a week. Starch-based films usually biodegrade in a week or less. Since starch is hydrophilic, the weight of the samples changed in response to fluctuations in soil moisture levels, which were influenced by meteorological factors. Soil organisms continue to ingest the bioplastics until they have entirely degraded, following their decomposition by moisture. Since starch is hydrophilic, moisture was essential to the entire degradation process and promoted soil microbial activity [37].

The findings demonstrate that the typical test procedure for soil biodegradation, which uses soil that is between 50% and 60% of its water-holding capacity, is presumably not optimised for soil water content, as evidenced by the faster biodegradation that occurs when the soil is at 80% of its capacity [38]. When compared to dry soil, bioplastic films tend to lose weight more quickly in wet soil. Wet soil fosters the growth of bacteria, which are essential for decomposing organic matter. Moisture content significantly impacts bioplastic biodegradation, affecting the physical structure and microbial activity during composting [39].

Effect of Biodegradation on Soil pH

Initially, an assessment of the field soil properties was conducted, followed by the implementation of the biodegradation process. The field soil had a neutral pH. Numerous studies have confirmed that maintaining soil pH levels between 7.5 and 7.8 creates optimal conditions for successful biodegradation [40]. The soil was measured using a Benchtop pH Meter - IC860033. The results of the investigation revealed that the soil had a high concentration of macroelements (N, P, and K). Mesoelements (Ca, Mg, and S) soil richness was low. However, the average level of B, Mn, Cu, Zn, and Fe microelements was present in the soil [41].

The weight loss trend in **Figure 5** indicates that the biodegradation rate of the banana peel bioplastic increases with ripeness. The highest percentage of weight loss occurs in overripe samples (23.38%), followed by ripe samples (22.71%) and unripe samples (18.36%) after a week. This phenomenon implies that overripe samples break down more quickly in neutral pH soil, most likely due to their softer texture and increased sugar content. Compared to ripe and overripe films, unripe films have less sugar. The breakdown of these may present more significant difficulties for soil microbes. Consequently, it may result in slower rates of biodegradation. Additionally, the pH of the soil can indirectly impact microbial growth and activity by influencing elements, including the availability of C substrate, nutrients, and metal cation solubility [42].

Effect of Biodegradation on Soil Temperature

Temperature substantially impacts materials characteristics such as physical, chemical, and structural properties. Materials can become softer and more pliable at higher temperatures [43]. Chandra and Rustgi [44] claim that temperature is a crucial component and influences polymer degradation, which rises in rate with temperature. Most investigations on polymers have been conducted at a temperature of 37 °C. For example, when exposed to higher temperatures, bioplastics degrade more quickly in this soil conditions [45].

All bioplastic films (unripe, ripe, and overripe) exhibit a distinct trend of increased biodegradation rates at 35 °C instead of 9 °C (**Figures 6** and **7**). Temperatures exceeding 35 °C are categorised as hot, while temperatures below 9 °C are classified as cold. After a seven-day soil burial test determined that biodegradation occurs most efficiently at 35 °C, with biodegradability rates of 29.89% for unripe, 29.91% for ripe, and 32.62% for overripe. In contrast, the weight loss at 9 °C for unripe, ripe, and overripe bioplastic films was 17.97%, 17.70%, and 23.73%, respectively.

According to Reed and Gilding [46], higher temperatures accelerated the degradation rate, most likely by encouraging the nonenzymatic hydrolysis of ester bonds. In this case, a high temperature and thermophilic microorganisms helped in early hydrolysis. Microorganisms that used the polymers as nutrition found that a temperature of 35 °C accelerated biodegradation. This trend highlights that microorganisms efficiently break down overripe samples, making their decomposition process significantly more effective. Fungi and bacteria are among several microorganisms that break down polymers in natural soils. Higher temperatures may favour microorganisms that survive in these environments and lessen competition from other bacteria and fungi [47]. These results indicate that high-temperature biodegradation is more efficient than low-temperature biodegradation. A more rapid biodegradation rate was observed for each type of bioplastic film at 35 °C. Research has indicated that the ideal circumstances for biodegradation are soil temperatures over 20 °C [48].

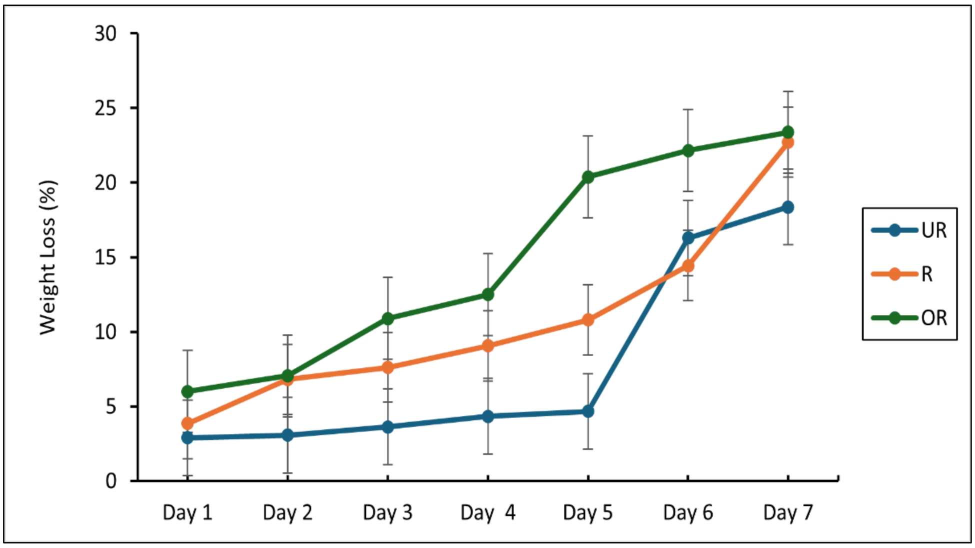

Figure 5. Soil burial test for the effect of soil pH.

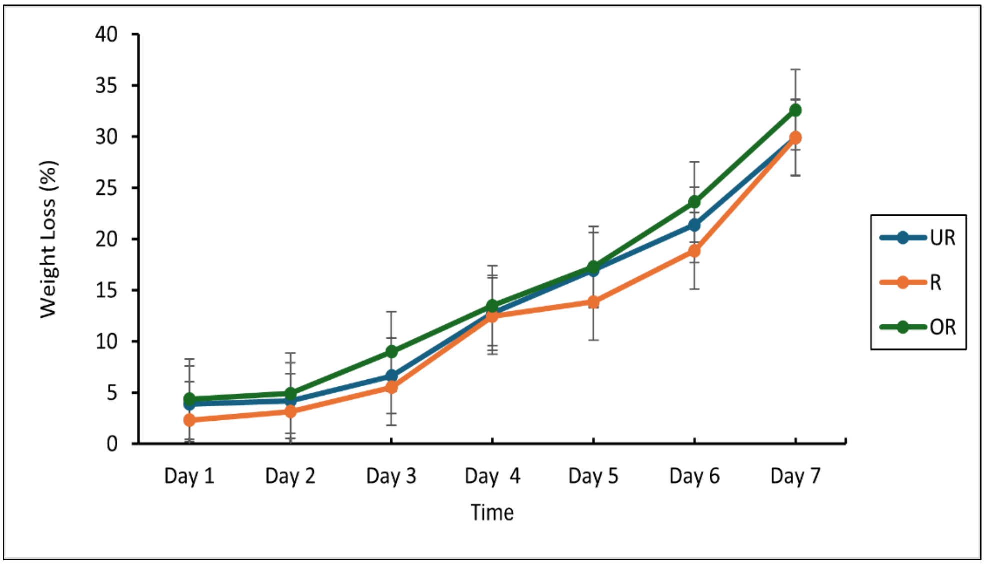

Figure 6. Effect of high temperature (35 °C) on biodegradation.

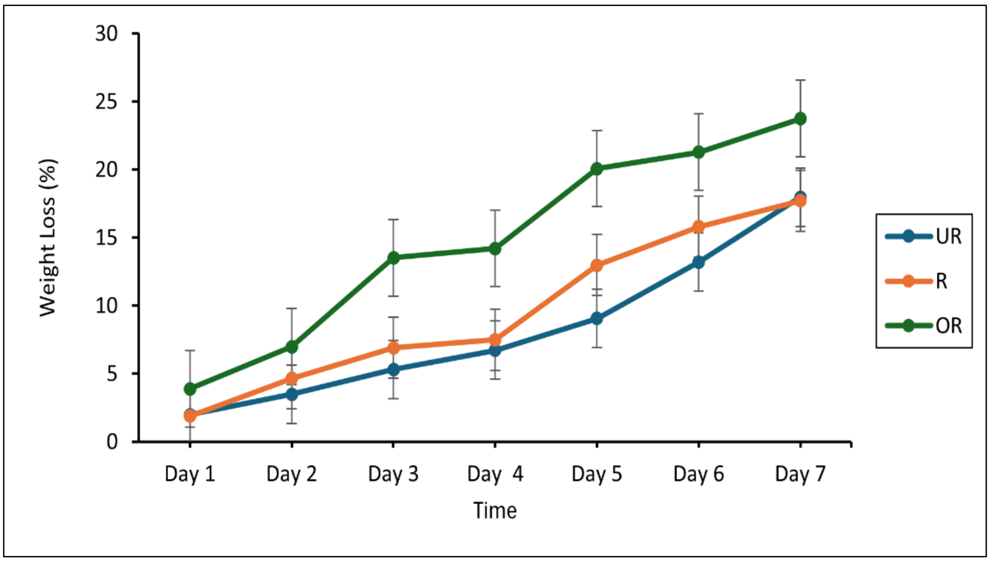

Figure 7. Effect of low temperature (9 °C) on biodegradation.

Aerobic Biodegradation Measurement Test

One of the primary metabolic products of an aerobic breakdown is CO_2, created when microbes oxidise the carbon (C) in organic material using oxygen [16]. Therefore, it is possible to utilise the percentage of biodegradation rate of bioplastic as an indicator for the amount of CO_2 emitted by microorganisms under the real-life conditions of the aerobic biodegradation process. **Figure 8** shows the weekly CO_2 emissions trend from unripe, ripe, and overripe banana peel bioplastics and the progression of their biodegradation rate over time. As the samples decomposed, the graph showed variations in CO_2 emission trends, correlating with the weekly percentage of the biodegradation rate. This trend reflects microbial activity in the soil involved in breaking down the bioplastic material. By observing the weekly changes in CO_2 emissions tied to the biodegradation rate, we can assess the degradation speed of each sample. Serving as an indirect indicator of microbial involvement, the CO_2 emission trend offers valuable insight into the bioplastic decomposition process illustrated in **Figure 8.**

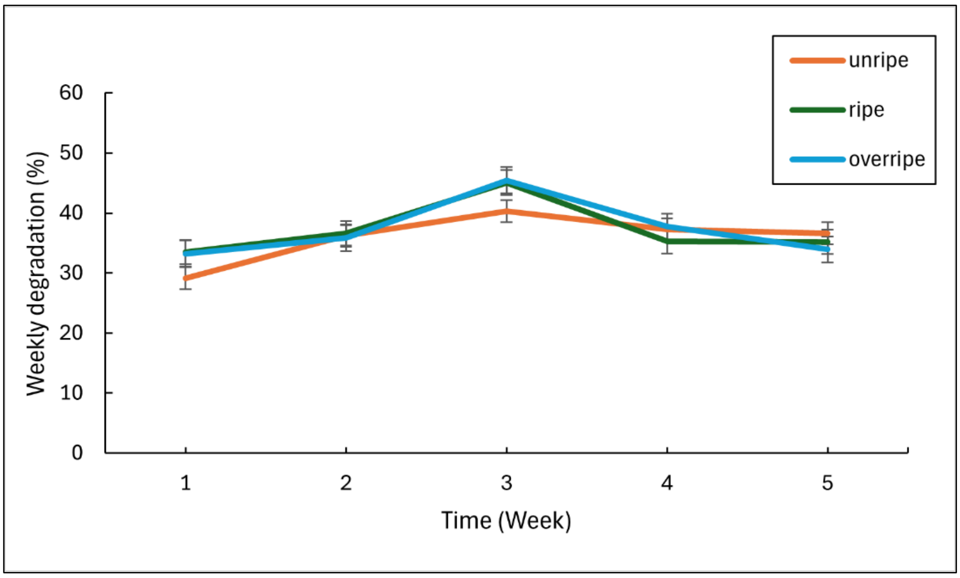

Figure 8. Weekly CO_2 emission.

The bioplastic film made of starch demonstrated an increasing trend; the ripe and overripe films degraded at a significantly higher rate, rising in the third week, whereas the unripe films degraded at a much slower rate, rising in the third week. The subsequent development of a biomass layer on the sample's accessible surface, which prevents enzyme diffusion and suppresses the enzymatic scission of starch-based film, is responsible for the sample's weekly biodegradation rate falling. It is reasonable to believe that the existence of bioplastic starch surfaces provided an appropriate pathway for the diffusion of microorganisms and their enzymes, which can speed up the biodegradation process, as an explanation for the behaviours of biodegradation [15]. Since the starch phase hydrolyses and metabolises slowly, the delayed biodegradation phase can be attributed to the CO_2 emission delay after the third week, as depicted in **Figure 8**.

According to Esmaeili et al. [15], the percentage of biodegradation rate in this measurement is determined by calculating the amount of CO_2 released during the breakdown of samples by microorganisms in the soil per the theoretical amount of CO_2. These films comprised glycerol and starch, which are completely 100% biodegradable. However, due to current environmental conditions, not all carbon content has been converted into CO_2 [16]. Some of the starch is expected to be broken down into monosaccharides, disaccharides, or smaller molecules that contain a carbonyl group.

CONCLUSION

In this work, bioplastic films made from powdered banana peels at various stages of ripening show significant variations in solubility, chemical composition, sensory qualities, and biodegradation rates. As a result of enhanced water interaction with ripeness, the films' solubility was highest in ripe samples (74.35%) and lowest in unripe samples (48.6%). With a weight loss of 32.62% at 35 °C over seven days, the overripe bioplastic film had the highest biodegradation rate, whereas the unripe film showed the lowest rate, at 17.97% at 9 °C. A faster degradation trend for ripe and overripe samples was also revealed by CO_2 emissions, underscoring the higher microbial activity linked to these films' higher sugar and moisture content. Overall, the results indicate that the biodegradability of bioplastics derived from banana peels is strongly influenced by ripeness, with overripe stages having the fastest potential for breakdown, especially in warmer, higher-moisture conditions.

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