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Biodegradable, Physical and Mechanical Characteristics of Banana Peel (*Musa Paradisiaca*) for Bio-plastics Polymer Composites

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ABSTRACT

Bioplastics became to meet high demand in plastic industries as its ability in performing biodegradable properties. Apart from that, this bioplastic particularly derived from banana peel and corn starch as to develop starch/biomass polymer composite. Thus, other commercial plastic takes a long time to fully or partially degraded. As a result, banana peel is chosen because of its abundant quantities to be obtained in Malaysia. The objective is to formulate TPS/BP polymer composites with different concentrations of BP and assess their mechanical and physical properties. The sample preparation involves multiple steps, including extracting BP through a maceration process and incorporating it into the TPS matrix to form the TPS/BP polymer complex. The findings reveal that TPS/BP composites with 10 wt% BP exhibit the highest tensile and tear strengths, reaching up to 39.303 MPa and 66.388 N/mm, respectively. In terms of biodegradability, the 40 wt% BP composite exhibits a higher degradation rate compared to the 5 wt% BP composites, with an average weight loss of 65.1% over 8 weeks, as opposed to the average weight loss of 45.2% in the latter case. Overall, TPS/BP polymer composites have shown significantly superior physical and mechanical performance, positioning them as a promising alternative to existing biodegradable polymers.

1. Introduction

Musa Paradisiaca, commonly known as the edible banana, is a hybrid resulting from the crossbreeding of two wild banana species, *Musa acuminate Colla* and *Musa balbisiana Colla*, both native to Southeast Asia. This research explores the significant potential of banana peel (BP) as a rich source of natural antioxidants and antimicrobial compounds, making it a promising candidate for the treatment of various diseases as stated by Hikal *et al.,* [1]. Additionally, the other research investigates by previous study [2], the value of banana by-products in recycling agricultural waste, presenting an excellent opportunity for the creation of raw materials in other industries. Indeed,

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further substantiates the extensive utilization of BP in food, pharmaceutical, and various other industries, including the production of biochemical products and inorganic waste management. The paper aims to shed light on the immense benefits and applications of banana peel, supporting its integration into sustainable practices across various sectors. Indeed, fruit waste uses to provide a sustainable and environmentally friendly source for the fabrication of biodegradable thin films, which could lead to the development of more environmentally friendly packaging materials.

Fruit wastes, including banana peel or skin, orange peel, pomegranate peel, and others, contribute significantly to biomass wastes, posing environmental challenges. Notably, bananas rank second as the most produced fruit globally, constituting 16% of the total fruit production worldwide, with an impressive 115.74 million metric tons produced in 2018. Remarkably, banana peels were account for 30-40% of the entire fruit weight which also amounts to approximately within 18-33% of the total fruit mass, leading to their classification as costly solid waste as states by [3]. This investigates the potential of converting banana peels and other fruit wastes into valuable biomaterials, such as biopolymers, biofuels, and biofibers, following the growing recognition of the importance of hazardous agricultural waste management. The research further explores and evaluates the findings from Solangi *et al.,* [4] and El Barnossi *et al.,* [5], providing critical insights into the significance of fruit wastes in biomass management and emphasizing the need for sustainable approaches to utilize these wastes for the production of bio-based materials that made up from natural resources which contribute to an eco-friendly and resource-efficient future. A diverse range of plastic thin films can be produced by incorporating various natural fibers as reinforcements and utilizing different matrices, leading to versatile materials with enhanced properties for applications such as packaging and biomedical uses.

Marichelvam *et al.,* [6] developed thin film plastic from rice starch and corn starch as a sustainable alternative to conventional plastics. The starch film exhibited promising mechanical properties. The tensile strength of the film was measured to be 12.5 MPa, indicating good resistance to stretching forces by sample with 7 g of rice starch and 3 g of corn starch. Additionally, its Young's modulus was found to be 0.183 GPa, suggesting its ability to retain shape and elasticity. However, in the tearing test between tapioca starch with palm, the film demonstrated a tear resistance of 22 N, highlighting its potential for durability by author [7]. Thus, this work highlights the potential of corn starch reinforced with banana peel to create eco-friendly thin film plastic with encouraging mechanical characteristics. Bioplastics also known as biodegradable plastics, offer a promising solution as they are derived from natural resources like corn starch, biomass, and food waste which degrade either entirely or partially, reducing their harmful impact on the environment. The addition of plasticizers as polymer additives in film blends with glycerol can enhance the physical and mechanical properties of bioplastics, improving their strength, flexibility, disintegration in soil conditions, surface morphology, and overall biodegradability reviewed by [8]. These plastics can be classified as thermoplastics and thermosets.

Thermoplastics are a class of plastic polymers that can be softened and melted through the application of heat. However, thermoplastic starch (TPS) exhibits poor mechanical properties, low tensile strength, lower density, and limited compatibility. Despite these drawbacks, TPS is commonly used in packaging, food, and agriculture films due to its low cost, biodegradability, and ease of regeneration. Polymer composites involve the reinforcement of fillers within a polymer matrix. The combination of natural and synthetic fibers with composite materials can significantly enhance the mechanical properties of the resulting composites showed in article by past research [9]. Next, Karimah *et al.,* [10] highlight the plant fibers, in particular, offer the advantage of low energy consumption during the manufacturing process, adequate strength, abundance, lightweight, and cost-effectiveness. In conclusion, addressing the abundant banana peel waste could benefit from

exploring bioplastics and thermoplastic starch as potential alternatives to conventional plastics. Utilizing polymer composites with natural fibers derived from banana peel waste can lead to sustainable solutions, reducing environmental impact and contributing to waste management efforts:

2. Methodology

2.1 Sample Preparation

This study focuses on the formulation of a TPS/BP polymer composite, using locally sourced raw materials like cornstarch and glycerin as a plasticizer, obtained from EvaChem, Taman Bukit Indah, Ampang, and Selangor, respectively. The banana peel (BP) filler for the polymer composites was acquired from a local stall at Jalan Panchor, Muar, Johor. Additionally, a commercial biodegradable polymer, supplied by Eco Botato Sdn. Bhd, derived from GMO-free corn starch, polylactic acid (PLA), and polybutylene adipate terephthalate (PBAT), was utilized. This polymer is suitable for both commercial and domestic composting, decomposing within 90 to 120 days depending on the compost environment, releasing organic substances like carbon dioxide and water without any toxic residues.

The work focuses on a preliminary investigation aimed at determining the appropriate concentrations of banana peel (BP) as a filler material for incorporation into polymer composites. The study initially considered ten different compositions of BP/CS thin film, as tabulated in Table 1. This study was investigating 5-40 wt.% BP filler.

Table 1
Preliminary composition of TPS/BP polymer composites

Filler		Matrix (Thermoplastic Starch)		
Concentration of Banana Peel Content	Banana Peel, wt. (%)	Corn Starch, wt. (%)	Glycerol, wt. (%)	Distilled Water, wt. (%)
5	5	5	1.5	73.5
10	5	5	1.5	73.5
15	5	5	1.5	73.5
20	5	5	1.5	73.5
25	5	5	1.5	73.5
30	5	5	1.5	73.5
35	5	5	1.5	73.5
40	5	5	1.5	73.5

The filler material obtained from the banana peel (BP) underwent a three-stage preparation process, including the drying, grinding, and extraction process. To assess its ability to retain moisture, the moisture content of BP was measured using the oven drying method, a widely used technique due to its adaptability to various material sizes and specifications. High-efficiency furnaces capable of reaching temperatures up to 250°C were utilized for this purpose, following the ASTM D2974-14 Standard Test Method for Moisture, Ash, and Organic Matter in Peat and Other Organic Soils as conducted by [11]. For the drying process, the BP was washed with distilled water to eliminate dirt and subsequently cut into small 2 ± 0.5 cm pieces (Figure 1a). These samples were then placed in a convection oven at 70°C for 24 hours (Figure 1b). Afterward, the tray was removed from the oven, and the dry weight of the sample was accurately recalculated. The dried BP was stored in an airtight container to ensure prolonged shelf life (Figure 1c). The study utilized BP sourced from the *Musa paradisiaca* species due to its widespread cultivation and richness in essential nutrients, such as

carbohydrates and proteins, which support microbial growth. Notably, Yadav *et al.,* [13] state the fresh fruit peels typically exhibit high moisture content, which influences their shelf-life duration.

(a) (b) (c)

Fig. 1. Drying process (a) Banana peels (b) Sample in oven (c) Dried banana peels

The dried BP was subjected to high-speed milling using a model number RT-34 mill shows in Figure 2(a)(b), with operating parameters set at 3450 rpm speed, 220-240 V voltage, and a filter sheet size of 0.3 mm. This milling process produced powdery foam particles with a diameter range of 0.23 ± 0.02 mm. The resulting ground BP was further sieved using a 212 µm mesh shaker to achieve a uniform particle size distribution of 0.23 ± 0.02 mm (Figure 2c). To ensure extended shelf life, the ground BP was stored in an airtight container. It is crucial to maintain a particulate size for the dried BP to attain maximum extraction yield.

The extraction process employed a maceration method, where in BP was immersed in ethanol at a 1:10 ratio of BP to ethanol for 24 hours. The resulting solution was filtered using Whatman grade 1 filter paper, yielding an extract of BP. For the fabrication of TPS/BP polymer composites, eight different concentrations of BP (ranging from 5 wt.% to 40 wt.%) were utilized. Maceration, a commonly used extraction technique, involves immersing plants in a liquid, such as alcohol, water, or oil, usually at room temperature. The choice of solvent depends on the specific chemical properties of the compounds present in the plant material. Alcohol, particularly, is a frequently employed solvent due to its ability to extract a wide range of molecules or active substances from the plant, including hydrophilic or water-soluble compounds, as well as lipophilic substances that dissolve in oils or other organic solvents [12]. The dry ground BP used in the study was prepared using the maceration method (Figure 2d). A mixture of corn starch (5 g), glycerin (1.5 g), and distilled water (88.5 g) was used to prepare the TPS matrix

(a) (b) (c) (d)

Fig. 2. Grinding process of banana peel (a) Grinder Machine (b) Grinding process (c) Ground banana peel (d) Extraction process of banana peel filler

As to prepare the TPS matrix, a mixture of corn starch (5 g), glycerin (1.5 g), and distilled water (88.5 g) was used. Initially, glycerin was added as a plasticizer to corn starch to form the matrix, followed by the addition of distilled water into the mixture. The combined solution was heated to 45°C and stirred slowly with a spatula for 30 minutes to ensure thorough mixing [13]. For this study, eight samples with varying filler concentrations (5 wt.%, 10 wt.%, 15 wt.%, 20 wt.%, 25 wt.%, 30 wt.%, 35 wt.%, and 40 wt.%) were prepared, selected based on preliminary investigations. Desired concentrations of BP were achieved for each sample by substituting a portion of the distilled water in the TPS matrix composition. The mixture was diligently stirred with a spatula to ensure proper homogeneity, free of lumps or bubbles. The resulting mixture was manually poured into a 7 cm x 5 cm mold, evenly distributed using a roller, and left to harden at ambient temperature for 48 hours as showed in Figure 3. Upon curing, the sample was removed from the mold, and its thickness was measured using a vernier caliper, recording the measurements. To evaluate their physical and mechanical properties, the TPS/BP polymer composites underwent various tests. The hand layup method was employed in this study, chosen for its minimal equipment requirements and cost-effectiveness in open molding. Raw materials were manually placed into the mold, and a roller was applied to ensure uniformity in the polymer matrix.

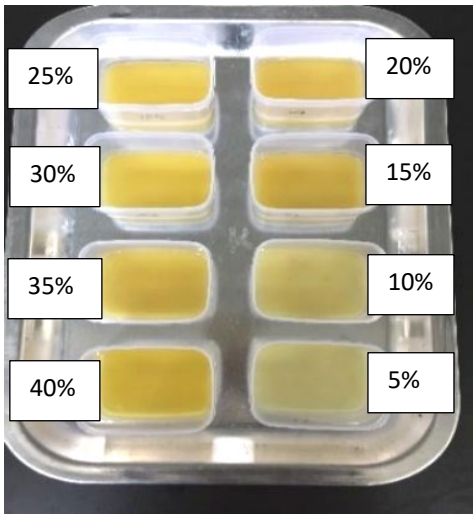


Fig. 3. TPS/BP polymer composites

2.2 Sample Testing

To obtain the TPS/BP polymer composite result, it was tested with several types of testing to identify the biodegradable, physical, and mechanical properties. For example, a Scanning Electron Microscope (Hitachi Regulus 8100, Japan) is a type of electron microscope that produces images of a sample by scanning the surface samples with a focused beam of electrons. In this study, SEM observed the microstructure and surface morphology thickness of TPS/BP polymer composites. It was used to identify the changes in the surface structure before and after the soil burial test within eight weeks and to observe the TPS/BP polymer composites' biodegradable properties.

Moreover, the soil burial test was used to determine the biodegradability properties of bioplastics samples after they were buried in compost soil at a 15 cm depth at the surrounding temperature. The degradation test was carried out using the ASTM D5988-18 Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials in Soil. Three specimens from each of the samples with different concentrations of BP filler, i.e. 5 wt. %, 10 wt. %, 15 wt. %, 20 wt. %, 25 wt. %, 30 wt. %, 35 wt. % and 40 wt.% were prepared. Firstly, each specimen's initial weight was determined

and recorded using an analytical balance. The specimens were then buried at a depth of 15 cm in the earth after a good amount of soil was poured into the container. The container was then exposed to the surrounding temperature for a period of 8 weeks to monitor and record the degradation process. The specimens' weight was determined again to determine the weight reduction in one week.

Next, the tensile strength test is the most fundamental mechanical test that may be carried out on experimental items. A tensile strength test is carried out to determine the maximum load, breaking force, and elongation at the break of the specimen. The specimen will split in half during the test, revealing the maximum tension force. The tool would display graphs and statistics illustrating the correlation between load and elongation, specimen area, Young's modulus, and stress and strain. At the Textile Laboratory, UTHM, the tensile strength was assessed using a model's universal testing machine (UTM) (lR 30KPlus Lloyd Instruments LTD, USA). The standard used was the ASTM D638 Standard Test Method for Tensile Properties of Plastics. However, three specimens from each sample with various BP concentrations have been prepared to perform this test. Before the samples were clamped at the clamping machinery, they were dimensioned (35 mm, 5 mm, and 0.2 mm) and cut into a "dog-bone" shape.

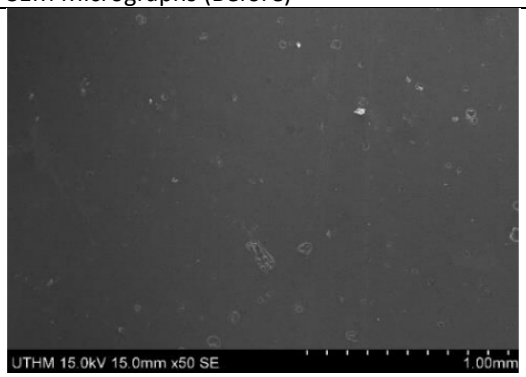
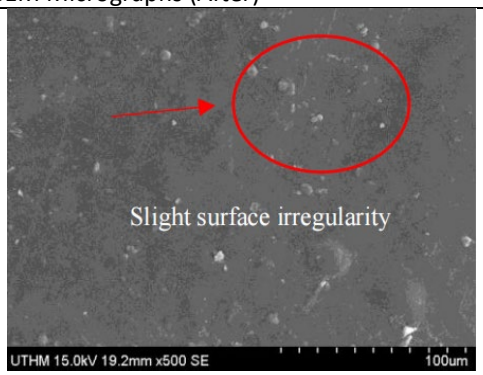
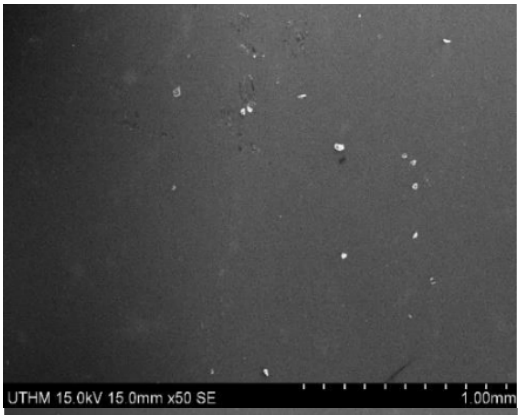
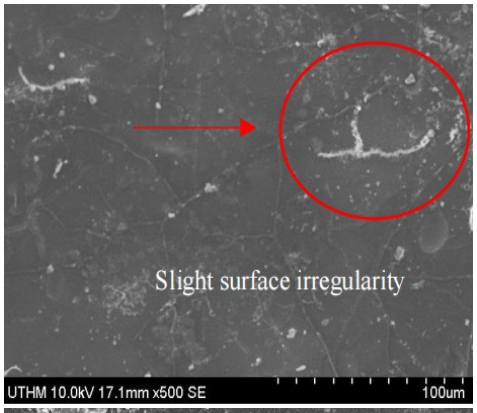
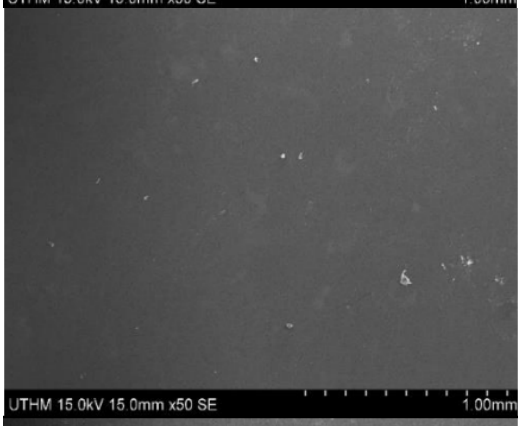
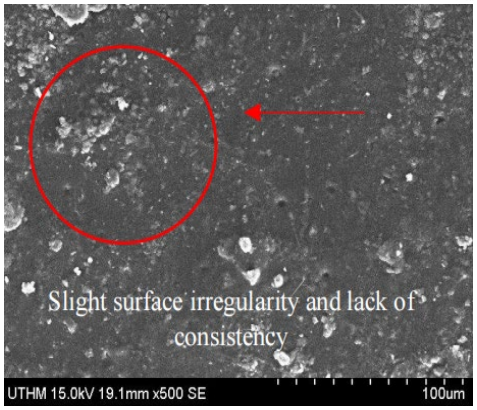
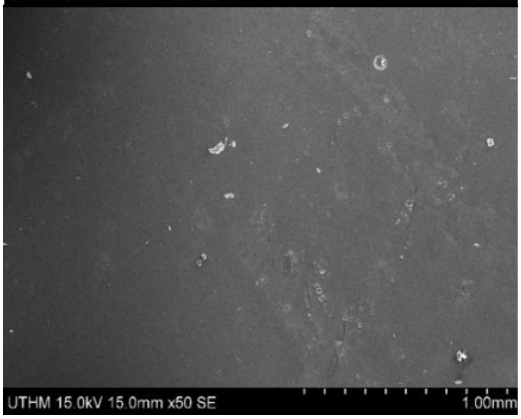
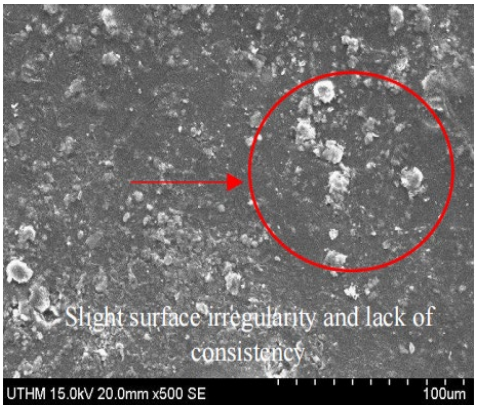
Apart from that, the "trouser shape" tear test includes splitting a rectangular specimen in half to generate two pairs of legs that resemble a pair of trousers. The specimen was then continuously pulled until it was entirely ripped apart and the tear had spread throughout it. Each leg was then attached to the test grips. According to the requirement, a small or large propagation force may have been preferred. The universal testing machine (UTM) model (LR 30KPlus Lloyd Instruments LTD, USA) was employed at the Textile Laboratory, UTHM, to evaluate the tear resistance. The test will be carried out by ASTM D1938 Trouser Tear of Plastic Film and Sheet by placing the test specimens into a tensile test or universal test machine, pulling up the section on one side of the fracture, and pulling down the section on the other.

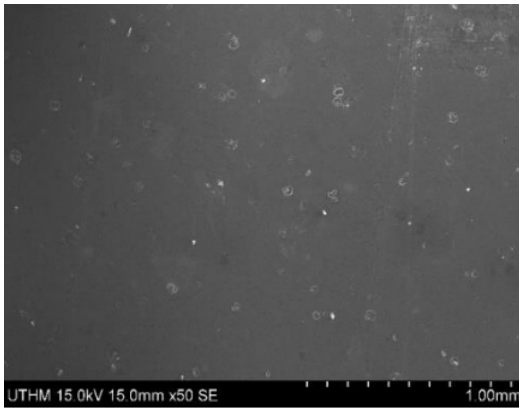
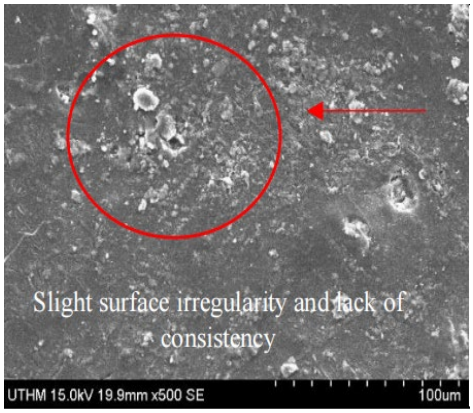
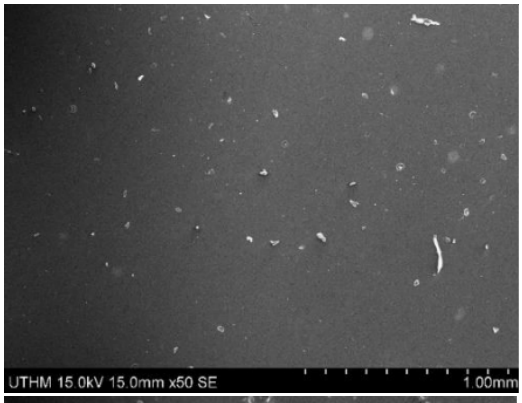
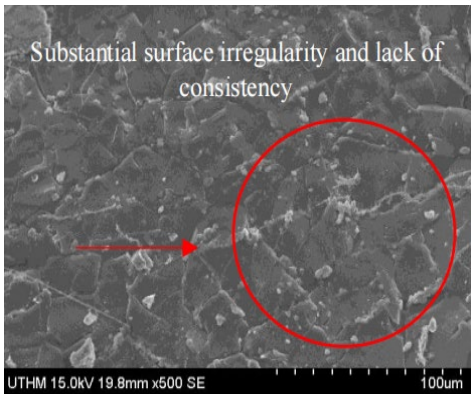
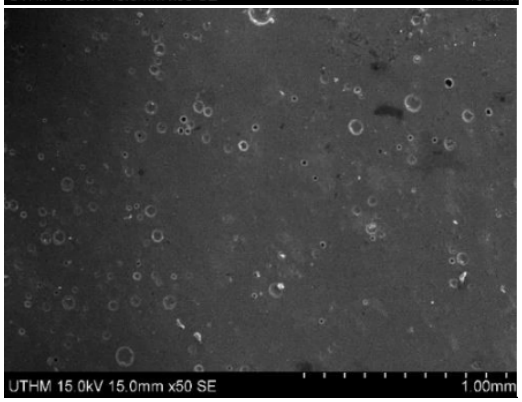
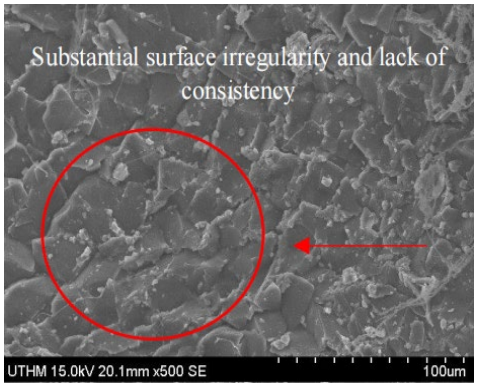
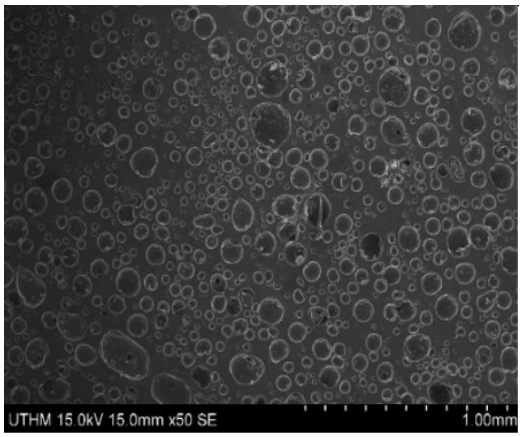
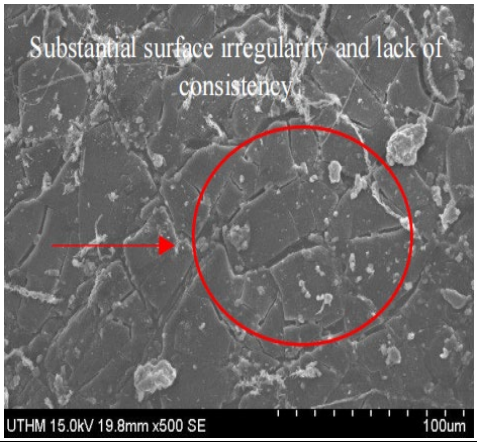
3. Results

3.1 SEM Analysis on TPS/BP Composites Biodegradability

The biodegradation process of TPS/BP polymer composites was monitored through scanning electron microscopy (SEM), systematically analysing the surface morphology of the samples after 8 weeks of soil runoff experiments. Table 2 displays the SEM images of all samples, illustrating significant changes in their structure. The SEM images revealed a microbial degradation behaviour where the material surface lost uniformity with increasing BP content in the composite. Specifically, sample A with 5 wt.% BP content displayed slight surface non-uniformity after the 8-week embedding process. The concentration of BP strongly influenced the biodegradation properties of BP/CS thin film. Furthermore, the SEM micrographs showcased the progression of the biodegradation process throughout the TPS/BP polymer composite, indicating the presence of defects and loss of polymer properties [14].

Table 2
SEM Micrographs of TPS/BP Composites Before and After 8 weeks

Samples	SEM Micrographs (Before)	SEM Micrographs (After)
5%		
10%		
15%		
20%		

25%	 UTHM 15.0kV 15.0mm x50 SE 1.00mm	 Slight surface irregularity and lack of consistency UTHM 15.0kV 19.9mm x500 SE 100um
30%	 UTHM 15.0kV 15.0mm x50 SE 1.00mm	 Substantial surface irregularity and lack of consistency UTHM 15.0kV 19.8mm x500 SE 100um
35%	 UTHM 15.0kV 15.0mm x50 SE 1.00mm	 Substantial surface irregularity and lack of consistency UTHM 15.0kV 20.1mm x500 SE 100um
40%	 UTHM 15.0kV 15.0mm x50 SE 1.00mm	 Substantial surface irregularity and lack of consistency UTHM 15.0kV 19.8mm x500 SE 100um

3.2 Visual Observation on the Biodegradability of BP/CS Composites

The macroscopic changes observed in the complex after the 8-week burial period are depicted in Figure 4. Over the course of eight weeks, visual observation revealed similar biodegradation patterns in all samples. Gradual degradation was observed, with the texture of the TPS/BP polymer composites visibly damaged, causing shrinkage and eventual tearing due to weight loss. These outcomes could be attributed to heightened microbial activity, extended burial durations, and increased material weight loss. Figure 5 shows the evident transformation in the specimens' physical appearance after the 8-week burial testing. Notably, black and brown spots appeared on the polymer surface, resulting from the growth and morphological changes of microorganisms. As the weeks progressed, the specimens underwent deformation, eventually forming a scaly appearance [15].

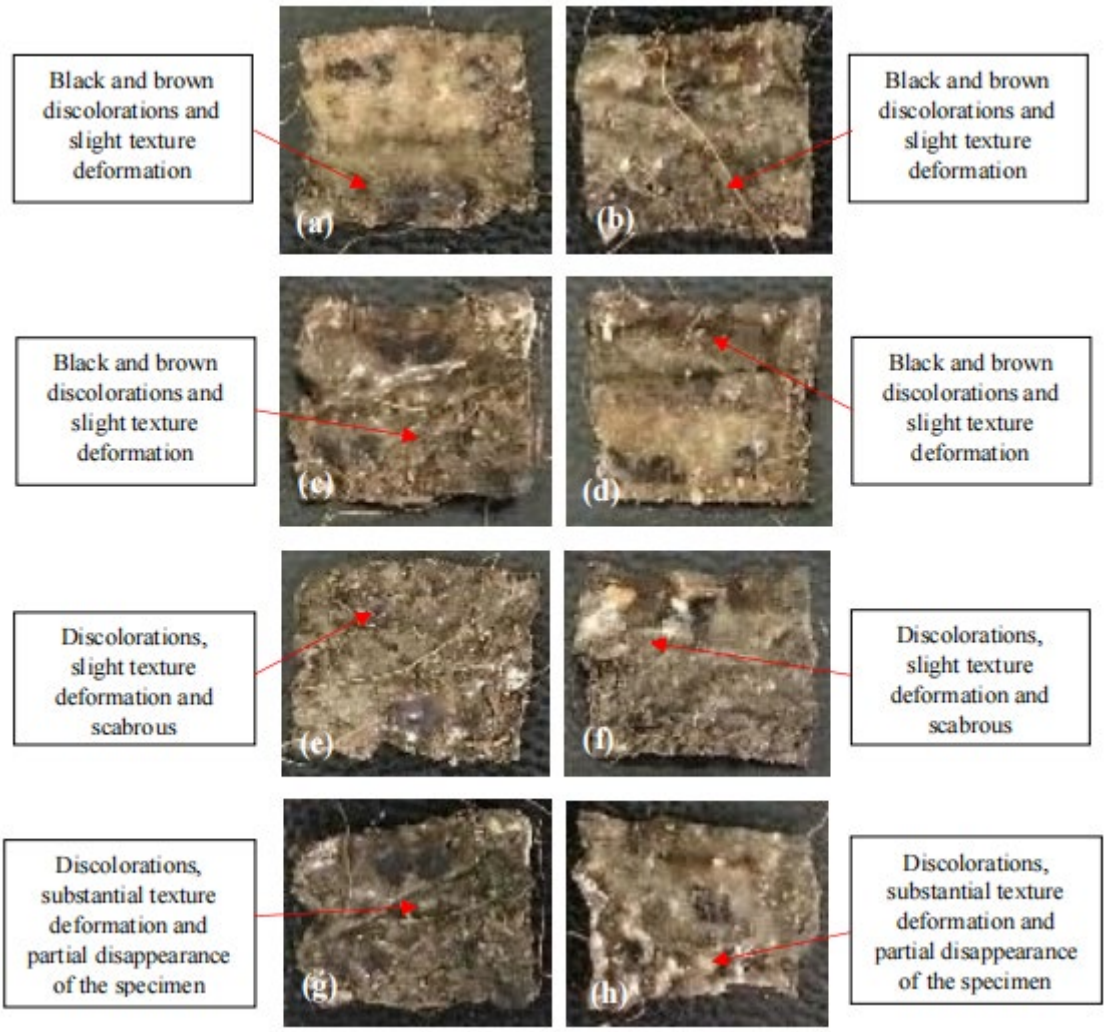


Fig. 4. Visual Observations from Soil Burial Test (a) week 1 (b) week 2 (c) week 3 (d) week 4 (e) week 5 (f) week 6 (g) week 7 (h) week 8

3.3 Biodegradable Test

The biodegradability of the TPS/BP polymer composites samples was assessed over 8 weeks through weight loss, visual observation, and SEM analysis. Weight loss served as the primary indicator of the biodegradation process during the burial stage. Figure 4 displays the average weight loss of all

samples over the 8-week period, revealing a consistent reduction in sample weight. The incorporation of BP into the TPS matrix contributed to enhanced composite degradation, signifying an improved biodegradation process. In most cases, the degree of weight loss decreased with increasing BP concentration.

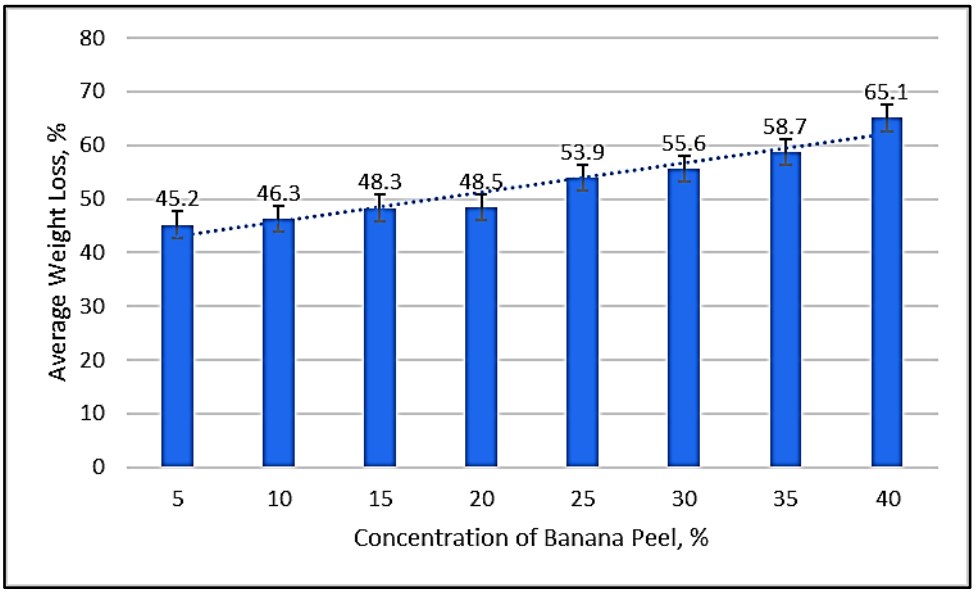


Fig. 5. Average Weight Loss Against Concentrations of Banana Peels

The addition of 5 wt.% to 40 wt.% BP led to weight reductions ranging from 19.8% to 24.1%, 17.1% to 20.5%, 9.2% to 24.2%, and 9.3% to 23.6% after 2, 4, 6, and 8 weeks of soil burial, respectively. The experiments with 40 wt.% BP exhibited the highest average weight loss of 65.1%, while those with 5 wt.% BP showed the lowest average weight loss of 45.2% after 8 weeks of soil burial. Additionally, samples with BP concentrations of 10 wt.%, 15 wt.%, 20 wt.%, 25 wt.%, 30 wt.%, and 35 wt.% displayed average weight losses of 46.3%, 48.3%, 48.5%, 53.9%, 55.6%, and 58.7%, respectively, over the 8-week period. The presence of high BP levels in the composites accelerated microbial degradation. In comparison, a commercial biodegradable polymer sample exhibited an average weight loss of 29.5% over 8 weeks, significantly lower than the average weight loss observed in TPS/BP polymer composites. These findings demonstrated that commercially biodegradable polymers have notably slower degradation rates compared to TPS/BP polymer composites [16].

3.4 Tensile Strength Test

The tensile strength test results are summarized in Figure 6. The sample with a BP concentration of 10 wt.% exhibited the highest tensile strength at 39.303 MPa, followed closely by the sample with 15 wt% BP concentration at 38.589 MPa. Tensile strengths for samples with BP concentrations of 5 wt.%, 20 wt.%, 25 wt.%, 30 wt.%, and 35 wt.% were 23.772 MPa, 30.635 MPa, 29.963 MPa, 23.055 MPa, and 20.856 MPa, respectively. On the other hand, the sample with 40 wt.% BP concentration displayed the lowest tensile strength of 15.538 MPa. These findings confirmed that the addition of BP improved the tensile strength of TPS/BP polymer composites. The tensile strength increased as the BP concentration increased from 5 wt.% to 10 wt.%, showing an improvement of approximately 28.8%. However, for BP concentrations ranging from 15 wt.% to 40 wt.%, the tensile strength decreased to the lowest levels. In contrast, the commercial biodegradable polymer sample exhibited a significantly lower tensile strength of 1.5 MPa compared to the TPS/BP polymer composite. Overall,

BP acted as a beneficial filler, enhancing the tensile strength of TPS matrices. However, it is crucial to carefully consider the filler amount when creating polymer composites, as the optimum concentration must be determined to achieve maximum tensile strength [17].

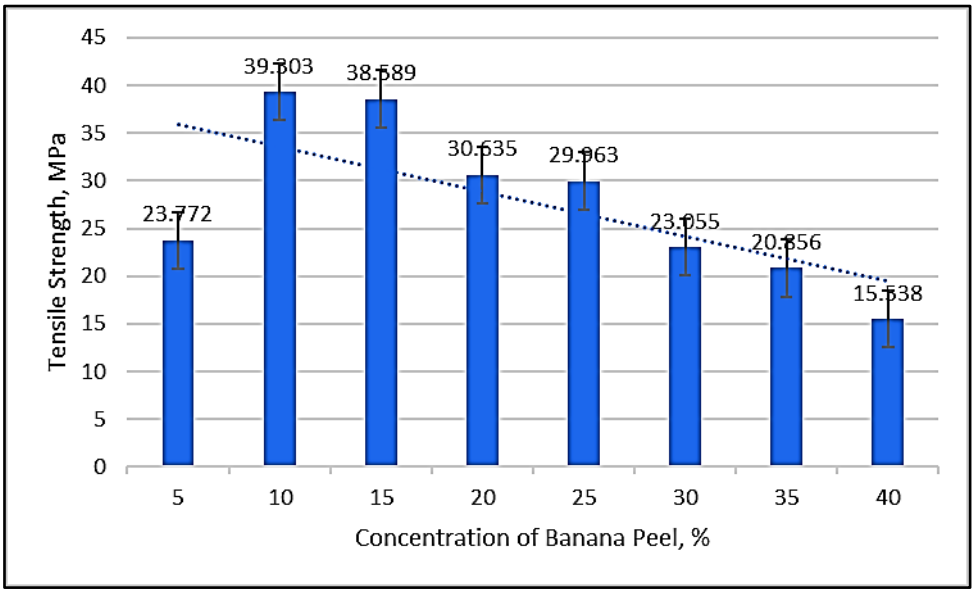


Fig. 6. Tensile Strength against Concentrations of Banana Peel

Figure 7 shows a plot of Young's modulus versus concentration of BP. This graph shows the change in stiffness of the samples, with the modulus increasing as the BP content in the composite increases. The 10 wt.% by weight sample had the highest elastic modulus at 31.048 MPa. On the other hand, the stiffness decreased dramatically to 13.609 MPa and continued the fluctuating trend up to the highest concentration of BP. Therefore, the higher the concentration of BP, the higher the stiffness of the composite. Nevertheless, the results exhibited by the TPS/BP composites indicate that the ideal concentration of BP is 10 wt.% and excessive BP content induces particle agglomeration of the filler within the TPS matrix, resulting in suggested that it causes a decrease in the stiffness of composites. Therefore, BP content played an important role for fabricating TPS/BP polymer composites with enhanced mechanical strength [19]. On the other hand, a commercial biodegradable polymer sample exhibited significantly lower stiffness compared to the TPS/BP polymer composite, at only 1.712 MPa.

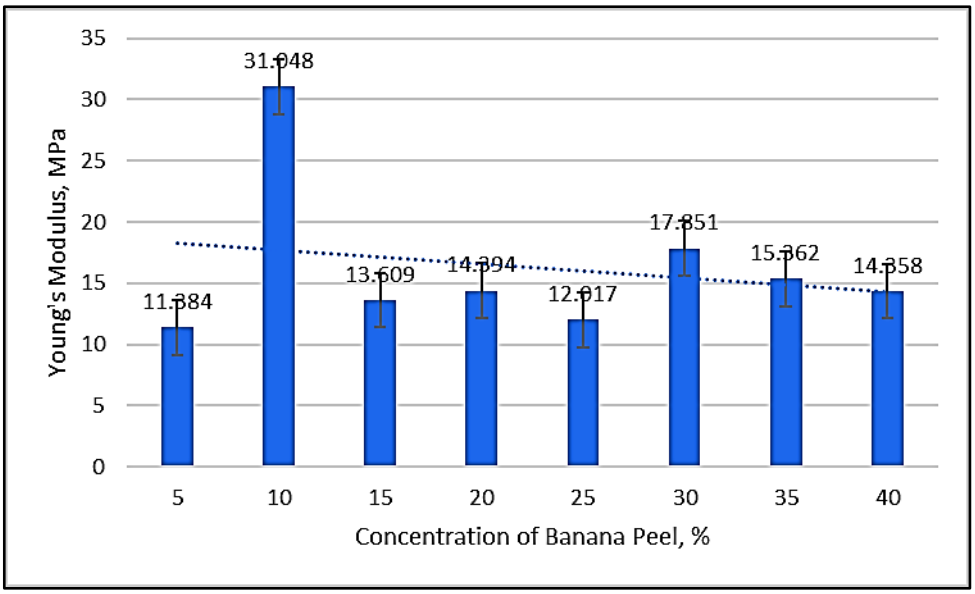


Fig. 7. Young's Modulus against Concentrations of Banana Peel

Figure 8 shows the stress-strain behavior of each sample with different concentrations of BP. From this stress-strain curve, it can be seen that the sample with 10 wt.% BP concentration exhibited the highest strength compared to the other samples. It was found that the sample with 10 wt.% BP concentration was very brittle and the sample with 40 wt.% BP concentration was the weakest and ductile.

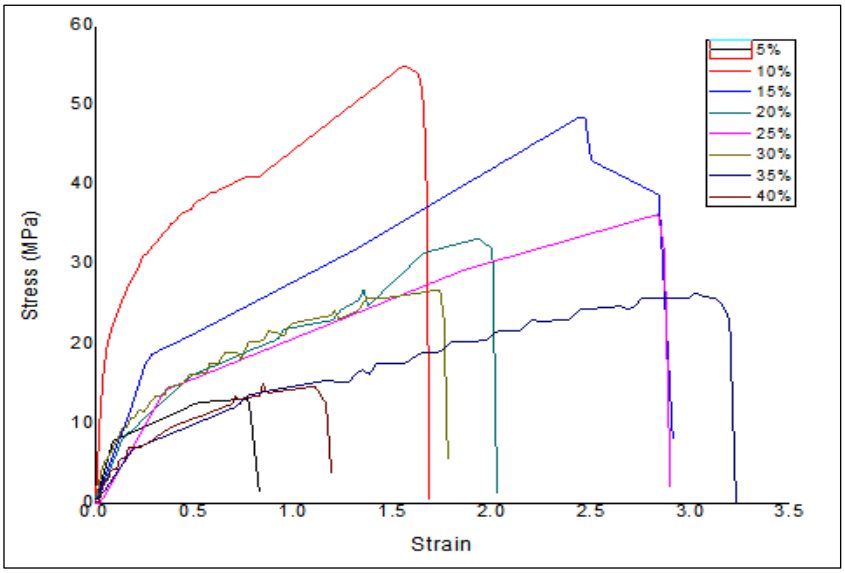


Fig. 8. Stress-strain Curve of BP/CS Polymer Composites

3.5 Tear Resistance Test

The tear resistance test results are presented in Figure 9. The sample with 10 wt.% BP concentration demonstrated the highest tear strength at 66.388 N/mm, followed by the sample with 15 wt.% BP concentration at 35.147 N/mm. Tear resistance for samples with BP concentrations of 5 wt.%, 20 wt.%, 25 wt.%, 30 wt.%, 35 wt.%, and 40 wt.% were 34.477 N/mm, 31.009 N/mm, 27.984 N/mm, 22.892 N/mm, 21.172 N/mm, and 21.117 N/mm, respectively. The graph reveals an increasing trend in tear resistance from 5 wt.% to 10 wt.% BP concentration, reaching the peak tear

resistance. However, the trend gradually declined, ultimately reaching the lowest value of 1.171 N/mm in the commercial biodegradable polymer sample (refer to Table 3). This indicates that the tear resistance of TPS/BP polymer composites was significantly higher than that of commercial biodegradable polymers. Notably, during the tear resistance test, the sample with 10 wt.% BP concentration displayed the shortest duration of crack propagation and minimal crack growth compared to the other samples. Thus, a BP concentration of 10 wt.% was identified as the optimal filler amount for resisting cracking in TPS/BP composites. Halimatul *et al.,* [18] explained that this condition arises due to the higher concentration of starch, resulting in increased tear resistance.

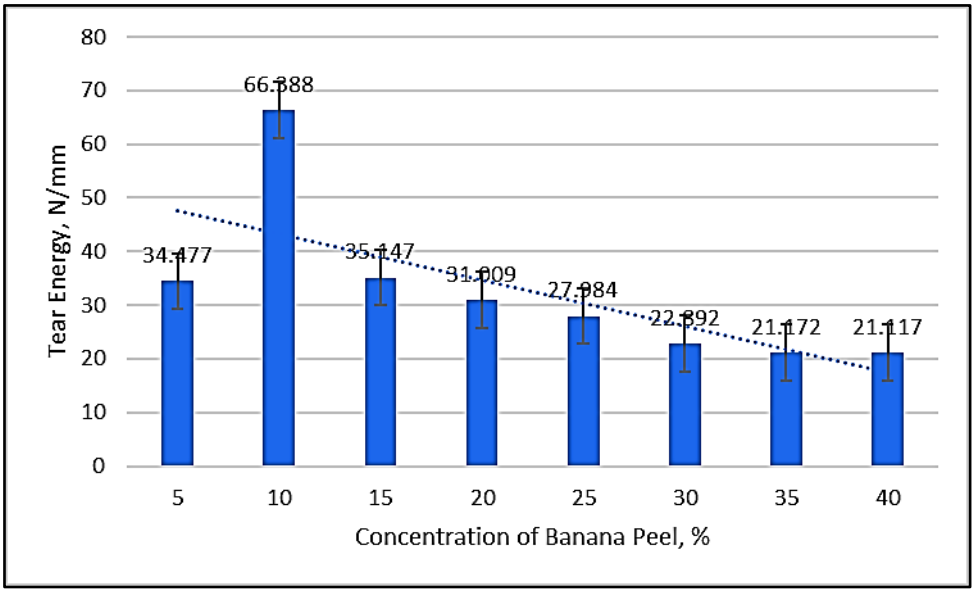


Fig. 9. Tear Energy against Concentrations of Banana Peels

3.6 Comparison Study

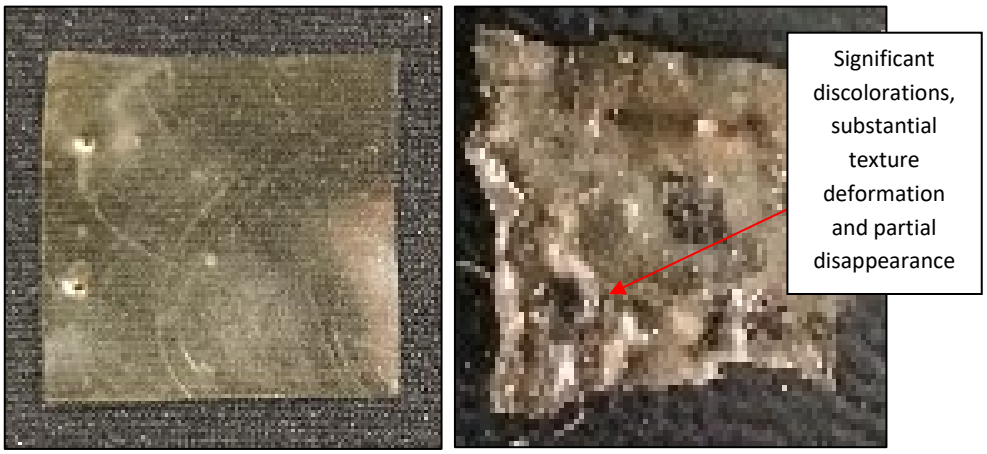
The comparison between TPS/BP polymer composites and commercial biodegradable polymers regarding their biodegradability and mechanical properties demonstrates the potential of TPS/BP thin film as an alternative to existing commercial biodegradable polymers. Table 3 provides a summary of the biodegradability in terms of weight loss and mechanical strength, specifically comparing sample B (10 wt.% BP) with commercially biodegradable polymers. According to the table, sample B exhibited an average weight loss of 46.3% over 8 weeks. In contrast, the commercial biodegradable polymer sample displayed an average weight loss of 29.5% over the same period. This significant difference indicates that TPS/BP polymer composites exhibited notably higher degradation rates compared to commercially biodegradable polymers.

Table 2
Comparison between TPS/BP Polymer Composites and Commercial Biodegradable Polymer

Samples	Biodegradability (Weight loss), %	Tensile Strength, MPa	Tear Resistance, N/mm
Sample B (10 wt. %)	46.3	39.303	66.388
Commercial	29.5	1.500	1.171

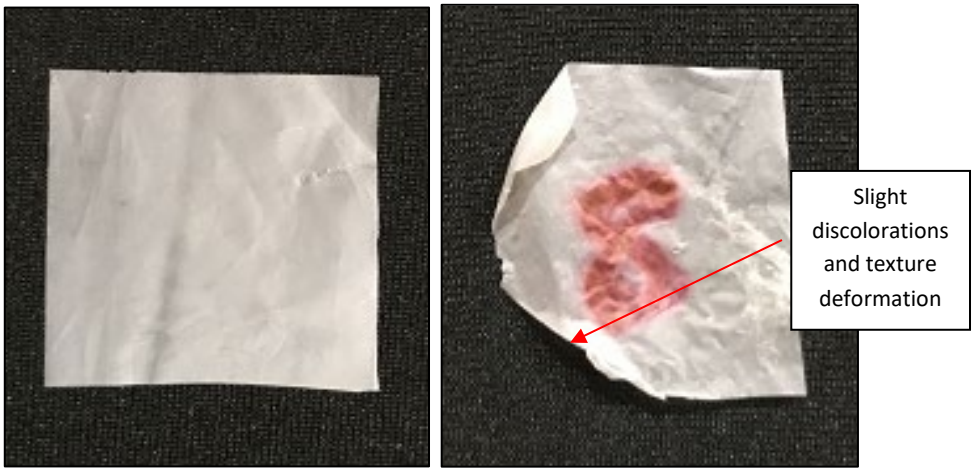
Furthermore, the physical appearance of the samples underwent evident changes after an 8-week soil burying test, as depicted in Figures 10 and 11. As the weeks progressed, the specimens gradually deformed, eventually developing a scaly texture. For instance, the sample B TPS/BP 10 wt.% BP

polymer composite exhibited significant discoloration, pronounced tissue deformation, and partial loss of the sample, as depicted in Figure 10. In contrast, the physical appearance of the commercial biodegradable polymers showed only slight discoloration and texture deformation after the soil burying test, as shown in Figure 11. These observations indicate a higher level of microbial activity on the surface of TPS/BP polymer composites and increased material weight loss compared to commercially available biodegradable polymers [19].



(a) (b)

Fig. 10. Visual Observations on Specimen B (a) Before Soil Burial Test, (b) After Soil Burial Test



(b) (b)

Fig. 11. Visual Observations on Commercial (a) Before Soil Burial Test, (b) After Soil Burial Test

Figure 12 presents the typical crack propagation and rupture observed during the tensile test. Experimental observations revealed distinct crack propagation behaviors and failure modes, resulting in noticeable differences in the failure surfaces of TPS/BP polymer composites and commercial biodegradable polymers. The fracture surface of the commercial sample (Figure 12b) appeared relatively smooth, facilitating easy and rapid crack propagation [11]. In contrast, the TPS/BP polymer composite exhibited a much rougher and slightly degraded fracture surface, featuring longitudinal cleavage with clear delamination of the filler-matrix interface (Figure 12a). The filler-matrix interface plays a crucial role in load transfer from the matrix to the filler in filler-reinforced composites [20,21]. Therefore, surface functionalization of BP fillers to enhance compatibility with the TPS matrix can contribute to improving the tensile strength of TPS/BP polymer composites.

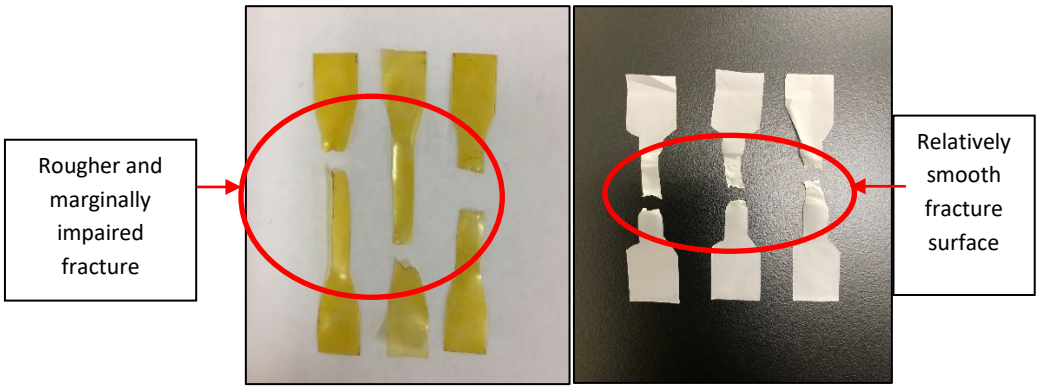


Fig. 12. Crack Propagation and Fracture of the Tensile Strength Test Process (a) BP/CS thin film (b) Commercial Biodegradable Polymer

Figure 13 illustrates crack propagation and rupture observed during the tear strength test. The nature of cracks is influenced by the applied force and material structure, as explained by Tan *et al.* [22]. Different tear patterns can occur depending on the direction and manner of force application, as well as whether the weak point extends from the edges or the middle of the material. Thus, this study aims to compare crack propagation and failure in TPS/BP polymer composites and commercial biodegradable polymers. For the tear strength test, pre-slit specimens were subjected to failure under monotonic loading. In the commercial sample (Fig. 13b), the crack propagated directly from the pre-slit tip. However, in the polymer composite sample (Fig. 13a), crack propagation was significantly influenced and slightly shifted to other regions. The inclusion of BP in the TPS matrix contributed to better stress distribution, hindering rapid crack growth at the tip before slitting. In BP/CS thin film, the loading force during stretching was initially absorbed by the TPS matrix and then transferred to the filler network [23]. As the load increased, the TPS matrix began to degrade, followed by filler failure, ultimately leading to material failure. Unlike commonly used rigid and brittle polymer matrices with relatively low elongation at break, the flexible TPS matrix in this study exhibited a greater capacity to withstand deformation forces [24].

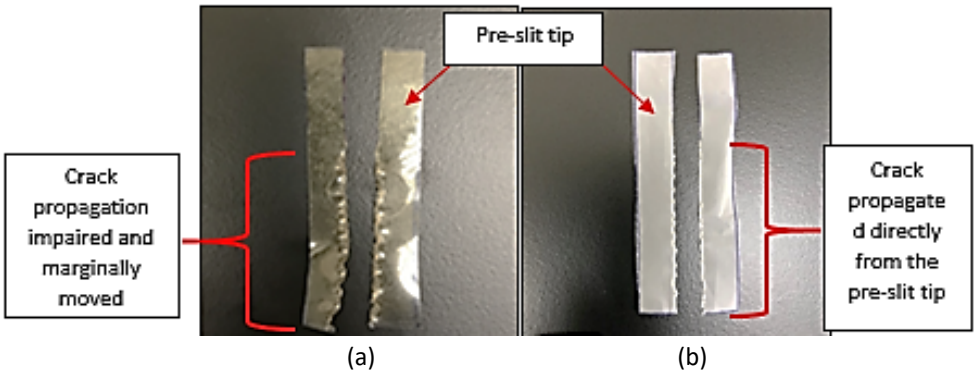


Fig. 13. Crack Propagation and Fracture of the Tear Resistance Test Process (a) TPS/BP Polymer Composite (b) Commercial Biodegradable Polymer

4. Conclusions

It can be concluded that the TPS/BP polymer composite containing 40 wt.% BP exhibited faster degradation than the one with 5 wt.% BP within the 8-week period, resulting in an average weight loss of 65.1%. The accelerated microbial degradation of bioplastics can be attributed to the higher

levels of BP, which provide abundant nutrients such as carbohydrates and cellulose, promoting a faster degradation process. The physical and mechanical properties of TPS/BP polymer composites outperformed commercially available biodegradable polymers. Notably, a BP concentration of 10% by weight displayed optimal and desirable mechanical performance when incorporated into the TPS matrix, yielding tensile and tear strengths of 39.303 MPa and 66.388 N/mm, respectively. Overall, this study is of great significance as it leads to improved properties of TPS/BP polymer composites. The results demonstrate that this TPS/BP polymer composite performs admirably in terms of physical and mechanical properties.

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