

ORIGINAL ARTICLE

Investigation on Tensile Strength, Tear Resistance and Biodegradable Properties of Thermoplastic Corn Starch (TPCS) Reinforced with Banana Peel (BP) as TPCS/BP Biodegradable Thin Film

Izzah Aqilah Ariffin¹, Noraini Marsi^{1,2*}, Iylia Izzati Jamal¹, Anika Zafiah Mohd Rus², Asmadi Md. Said³

¹Faculty of Mechanical Engineering Technology, University Tun Hussein Onn Malaysia (UTHM), Hub Pendidikan Pagoh, KM 1, Jalan Panchor, 84600 Pagoh, Muar, Johor, Malaysia

²Advanced Manufacturing and Material Centre (AMMC), Universiti Tun Hussein Onn Malaysia (UTHM), Parit Raja, 86400 Batu Pahat, Johor, Malaysia

³Angkasa Kowaris Plastics Sdn Bhd, Lot 15796, Block A & B, Jalan Kebun Tambahan, Seksyen 32, 40460 Shah Alam, Malaysia

mnoraini@uthm.edu.my

Abstract. Malaysia was recognized as the second-largest plastic consumer in Asia, with an average consumption of 16.78 kg per person. This high demand for commercial plastics has spurred interest in biodegradable alternatives, such as those derived from natural resources like banana peels. This research focuses on developing thermoplastic corn starch (TPCS) reinforced with banana peel (BP) to create TPCS/BP biodegradable thin films. The main objective is to evaluate these films' physical, mechanical, and biodegradable properties at various TPCS/BP concentrations. The fabrication involves drying banana peels in a universal oven at 70 °C, grinding them into powder with a particle size of 0.23 ± 0.02 mm, and extracting them using the maceration method. The extracted BP, at concentrations ranging from 5 to 40 wt.%, was mixed with 5 wt.% corn starch, 2 wt.% glycerol, and 15 wt.% polyvinyl alcohol (PVA), then cured at room temperature (24 °C) for 72 hours to produce the films. Results showed that BP powder had a moisture content of 91.31%. Among the different formulations, the 10 wt.% TPCS/BP film exhibited the highest tensile strength (75.53 MPa) and tear resistance (50.77 N/mm). The biodegradable test indicated a degradation rate of 5.99%, while density and porosity were 0.48% and 1.81 g/cm³, respectively. However, SEM analysis proved as the concentration of TPCS/BP increased, the surface became more homogenous, with 40 wt.% having more homogenous distribution and a higher irregularly surface than 5 wt.% with a lower slight uniformity surface. Thus, 10 wt.% TPCS/BP is identified as the optimal concentration for biodegradable thin film applications with good mechanical properties.

1. Introduction

The market for biodegradable plastics is expanding rapidly due to rising environmental awareness, regulator pressure, and customer desire for sustainable products. Anugrahwidya et al., [1] demonstrated that inventive composite materials, such as those comprising natural fibers, can improve bioplastic's

mechanical characteristics and biodegradable properties, raising commercial appeal. 81% of respondents globally remain convinced that manufacturers or commercial entities should contribute to sustainability improvement [2][3]. Manufacturers are obligated by the increase in consumer preferences to use biodegradable materials in packaging and other uses to improve brand image and fulfill market expectations with a growing number of people looking for eco-friendly items [4]. Natural resources can be replaced in plastic making because of their biodegradable properties. Other than biodegradability properties, its mechanical durability, barrier characteristics, thermal resistance, processing ability, biocompatibility, and low environmental impact have been considered in developing biodegradable thin films. Due to such properties, it has the potential for a broad range of applications, including consumer products, packaging, agriculture, and biomedicine, contributing to a more sustainable environment. The main contributors to biomass waste were fruit waste, which included banana peel, orange peel, pomegranate peel, and other fruits [5].

In Malaysia, significant quantities of fruit peels are generated from the annual production of bananas (37%), oranges (3%), pineapples (40%), mangoes (4%), and papayas (6%), with peels comprising substantial portions of each fruit. These peels, rich in valuable bioactive compounds and nutrients, offer the potential for creating sustainable products and reducing agricultural waste [6][7]. Fruit waste tends to be difficult to dispose of unless treated appropriately. Poor disposal techniques, including open dumping or incorrect composting, can cause the anaerobic breakdown of waste materials to release methane, a strong greenhouse gas. Bananas are the second most produced fruit globally, accounting for 16% of worldwide fruit production [8]. Banana peels and other organic waste significantly contribute to methane emissions from landfills worldwide [9]. Furthermore, poorly dumped banana peels can cause local nuisances, attract bugs, and bring hygiene problems to urban areas.

Banana peels are rich in cellulose, hemicellulose, and lignin, making them suitable candidates for producing biodegradable materials. Utilizing banana peels to develop bioplastics helps manage waste and adds value to what would otherwise be a discarded byproduct. This approach aligns with the principles of a circular economy, where waste materials are repurposed into valuable products, reducing the overall environmental footprint. Incorporating banana peel fibers into starch-based films significantly enhances their mechanical properties, such as tensile strength and elasticity, making them viable alternatives to conventional plastics [10]. The tensile strengths of 12.84 MPa were achieved through the study of thin films developed from corn husk fibers and corn starch/chitosan filler mixtures with 0-8% chitosan content discovered better mechanical characteristics with potential antibacterial benefits [11]. Date palm leaf filler (0–40 wt.%) with PVA found less biodegradability but increased tensile strength of up to 17.68 MPa [12]. Thus, the pressing need to address banana peel disposal issues has driven innovative research and development efforts toward creating natural-based, biodegradable materials that are both environmentally friendly and economically beneficial.

2. Literature Review

The development and implementation of biodegradable starch-based polymers such as oil shortages and a rising desire to reduce the environmental effect of broad petrochemical polymer use. In response to these issues, starch-based products now contain a variety of natural fillers and edible reinforcing agents, including natural fibers, starch or cellulose crystals, and extract. Furthermore, starch-based composites have been developed using self-reinforced methods, including modified starch particles to strengthen the starch matrix. Humans have been using natural fibers from plants, animals, or minerals for ages for various purposes. These fibers encourage eco-friendly practices in sectors including composites, building, and textiles by offering a sustainable and renewable substitute for synthetic materials. Natural fibers nevertheless have several advantages over synthetic fibers, even though their tensile strength may not be as high [13].

The polymer matrix and fillers are reinforced to form plastic polymers. Two or more materials with different properties are combined in composite materials, called the matrix and reinforcement [14]. The mechanical characteristics of composite materials are improved using natural and synthetic fibers. Plant

fibers, in particular, have a low energy need and sufficient strength. These fibers also have the advantages of being widely available, inexpensive, and lightweight, enhancing overall performance [15]. Bangar et al., [16] highlighted the significance of improving the compatibility of natural fibres with the polymer matrix, as well as the impact of additives in increasing interfacial adhesion and dispersion. However, further research is required in order to clarify the fundamental mechanisms and enhance the formulation for enhanced efficiency. The properties of polymer materials may be modified and improved by incorporating synthetic biopolymers, which offer special functions to meet various application needs. Among these additions, polylactic acid (PLA) and polyvinyl alcohol (PVA) stand out because of their unique qualities and uses.

Polyvinyl alcohol (PVA) and other synthetic water-soluble biopolymers have attracted a lot of interest from a variety of sectors because of their special qualities and broad range of uses. The synthesis, characterization, and uses of PVA have been the subject of recent research, highlighting its potential advantages and pointing up areas for further study. The synthesis and modification of PVA to customize its characteristics for certain uses is an important field of study. Particularly, to increase the solubility, biodegradability, and mechanical characteristics of PVA, innovative synthesis pathways and chemical modifications have been investigated, addressing the need for improved synthetic procedures and functionalization strategies [17][18]. Polyvinyl alcohol (PVA) is widely used in many different applications, such as adhesives, biomedical devices, and packaging films, because of its outstanding chemical resistance, high strength, and biocompatibility. PVA and starch combine to form a miscible one-phase mix because to its polar nature and compatibility with starch. Moreover, it has been demonstrated that adding PVA to thermoplastic starch improves the mechanical qualities of foams [19].

Biodegradable plastic thin-film fabrication processes employ a variety of ways to produce films with specific functions. Solvent casting is a widely used process in which a thin film is formed by casting a solution of biodegradable polymers and additives onto a substrate and then drying it. This process makes it possible to precisely regulate the film's composition and thickness, making it perfect for creating homogeneous films with certain characteristics. Solution casting is a versatile and effective method for producing biodegradable films from starch-based polymers [20]. In order to create a thin film, solution casting entails dissolving the biodegradable polymer in the proper solvent, pouring the solution onto a flat surface, and then waiting for the solvent to evaporate. There is a great deal of variety in altering the thickness and composition of the film using this process.

Biodegradable plastics require careful component and additive balance throughout design to achieve desired properties and maintain environmental sustainability. A common option is employing a mixed design strategy that includes various biopolymers, fillers, plasticizers, and other additives to improve the material's performance and biodegradability. It is important to choose the right biopolymers since they all have distinct qualities that may be customized to fit the demands of various applications, including mechanical strength, flexibility, and biodegradability. This technique makes it possible to produce biodegradable polymers suitable for certain applications, maximizing their sustainability and efficiency.

3. Methodology

A preliminary study was conducted to determine the concentration of BP as a suitable filler material for reinforcement into polymer composites. Eight compositions were initially used to create the TPCS/BP biodegradable thin film as shown in Table 1. The composition of the TPCS/BP was selected based on previous research studies. This composition was chosen to obtain TPCS/BP thin films with good physical and mechanical enhancement by considering each material property.

Table 1. Percentage composition on the mixture of banana peels and binder corn starch.

Samples of TPCS/BP	Material		Matrix (Thermoplastic Corn Starch)		
	Banana Peel Extraction wt. (%)	Corn Starch wt. (%)	Glycerol wt. (%)	Distilled Water wt. (%)	PVA wt. (%)
5%	5	5	2	38	50
10%	5	5	2	38	50
15%	5	5	2	38	50
20%	5	5	2	38	50
25%	5	5	2	38	50
30%	5	5	2	38	50
35%	5	5	2	38	50
40%	5	5	2	38	50

Three primary steps are involved in banana peel extraction preparation in developing TPCS/BP biodegradable thin films, which are drying the peels, grinding the dried peels, and extracting the ground material [21]. At first, the banana peels are properly dried at 70°C for 24 hours to eliminate moisture [22]. The dried peels are then uniformly ground into a fine powder. The extracted filler was dried to determine its chemical profile, including the presence of carbohydrates, dietary fibre, proteins, and bioactive compounds such as antioxidants and antimicrobial agents [23][24][25]. The average area of BP particles in ten regions is 0.012 mm², and the particle size range is 0.0151 – 0.0210 mm². The ground BPs underwent a sieving shaker with 212 µm mesh to acquire a powder form particle size. Then, the banana peel filler was extracted through a maceration process for 24 hours, which involved soaking the peels in 99% ethanol to facilitate the separation of the fibrous and cellular components [26]. The desired bioactive compounds are finally extracted from the ground banana peel and added to the biodegradable thin film matrix.

The preparation of thermoplastic corn starch (TPCS) with the addition of polyvinyl alcohol (PVA) involves a systematic process to create a homogeneous and biodegradable polymer matrix. First, 5 g of corn starch is mixed with 2 ml of glycerol, a plasticizer that increases the corn starch matrix's elasticity. The mixture is subsequently mixed with 50 ml of PVA solution and 38 ml of distilled water. The mixture is then heated to 45°C while slowly stirring with a spatula to enable the PVA to dissolve and completely integrate with the glycerol and corn starch for 30 minutes [27]. Glycerol is a useful plasticizer that may be used to improve the mechanical characteristics and processability of starch-based materials [28].

Eight samples with different filler concentrations (5-40 wt. %) have been prepared, as shown in Table 1. The preparation of eight samples with varying filler concentrations was done by using the solvent casting method, which involves a detailed and precise process to ensure uniformity and consistency. Initially, the required amounts of banana peel powder for each concentration level (5%, 10%, 15%, 20%, 25%, 30%, 35%, and 40%) are calculated relative to the total weight of the mixture, and eight separate batches are prepared. The homogeneous mixture has been poured onto a flat casting surface or into molds with size 15 cm x 10 cm for the curing and hardening process.

4. Result and Discussion

4.1. Moisture Content of Banana Peel

Based on a sample size of 100 ± 0.9 grams, the results showed that the BP had about 91.31% moisture. This high moisture content shows that BP retains a large quantity of water, which can have a considerable influence on its processing and use in a variety of applications. The results and analysis data were justified based on the previous research study. High moisture content in biomass materials can cause deterioration and microbiological development, as well as complicate processing and grinding. As a result, reducing moisture content is critical for improving stability and ease of handling. The oven drying process is recommended to reduce the moisture content of BP to more manageable levels, specifically down to 8.69%, as indicated by the analysis of dehydrated BP. This study compared commercial biodegradable thin film's physical and mechanical properties and TPCS/BP biodegradable thin film.

It is essential to properly dry BP to maximize its qualities and guarantee durability for later uses, including making biodegradable films. Reduced moisture content facilitates smaller particle size during the grinding process, which is advantageous for producing a homogeneous and consistent material [29]. This consistency is especially crucial for applications like thermoplastic starch-based films that employ BP as a filler or reinforcing ingredient in biopolymer matrix. Maintaining a low moisture level allows the BP to be efficiently incorporated into the polymer matrix, improving the composite material's mechanical characteristics and overall performance. Furthermore, appropriate drying helps to eliminate any potential unfavorable interactions between residual moisture and other components throughout the fabrication process, assuring the maximum possible yield and quality [30].

Table 2. Moisture content in 100 ± 0.9 grams of BP

Samples	Wet weight, (g)	Dry weight, (g)	Moisture Content, (%)	Average Moisture Content, (%)
1	100.488	8.553	91.49	91.31
2	100.579	7.876	92.17	
3	100.236	9.335	90.69	
4	100.149	9.963	90.11	
5	100.135	7.944	92.07	

4.2. Density and Porosity

The analysis of the TPCS/BP biodegradable thin films reveals a significant relationship between the concentration of banana peel (BP) extraction and the resulting density and porosity of the samples. As illustrated in Figure 1, the density of the samples shows a clear trend of increasing with higher concentrations of BP extraction. The highest density recorded was 2.532 g/cm^3 in the sample with 40 wt.% BP concentration, while the lowest density was 1.687 g/cm^3 in the sample with 5 wt.% BP concentration. This trend can be attributed to the increased incorporation of BP, which likely enhances the packing density and reduces the void spaces within the matrix, leading to higher overall density. It has been demonstrated that a higher filler content corresponds with a higher density in natural fiber composites, where density is formed by the effective dispersion and interaction of filler particles inside the polymer matrix.

On the other hand, the porosity and density of the biodegradable thin films made of TPCS and BP exhibit an inverse relationship. The porosity decreases with increasing density, as seen by the greatest porosity of 0.594% in the 5 wt.% TPCS/BP sample and the lowest porosity of 0.159% in the 40 wt.%

TPCS/BP sample. The reduction in porosity with increasing BP concentration implies that the filler material efficiently fills the spaces within the polymer matrix, resulting in a denser and less porous structure [31]. Lower porosity often enhances mechanical performance, resulting in fewer flaws and better stress distribution. Furthermore, reduced porosity can improve the barrier qualities of the films, making them more suited for various industrial applications, including packaging and agriculture [32]. Developing high-performance biodegradable materials depends on the interaction between density, porosity, and mechanical characteristics [33][34].

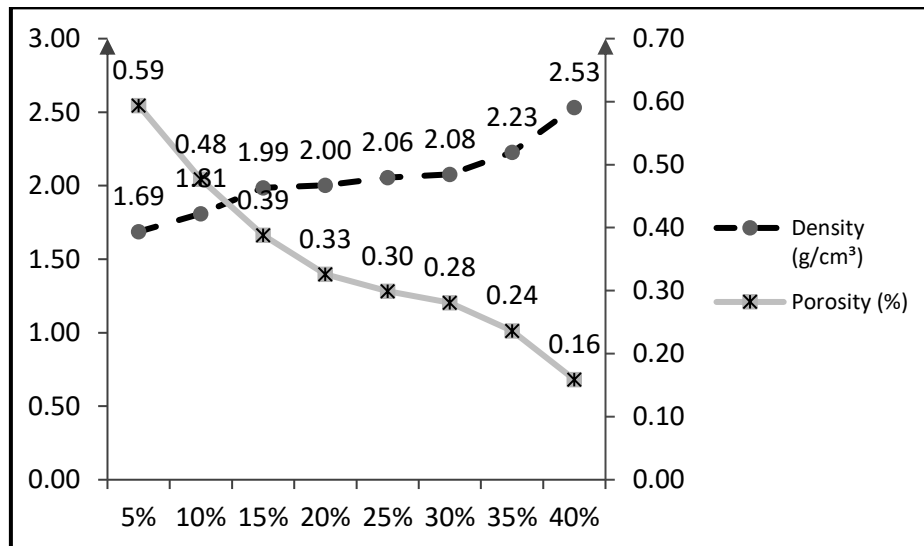


Figure 1. Density and porosity against concentration of banana peel (%)

4.3. Tensile Strength Analysis

The graph presented in Figure 2 illustrates a significant correlation between the tensile strength of TPCS/BP biodegradable thin films and the concentration of banana peel (BP) filler. The sample with a 10 wt.% BP content had the maximum tensile strength, 75.53 MPa. This peak in tensile strength indicates that the 10 wt.% BP concentration provides the optimum proportions of reinforcement inside the TPCS matrix, which is probable due to the strong bonding and dispersion of BP fibers within the polymer. This concentration may improve the interface between the starch matrix and the BP fibers, thus enhancing load transmission and mechanical characteristics. However, as the BP concentration exceeds 10 wt.%, the tensile strength declines gradually, with the lowest value reported at 24.18 MPa for the 40 wt.% BP sample. This decrease in tensile strength at greater BP concentrations might be related to the agglomeration of BP particles, which can function as stress concentrators and break down the composite structure [35].

The uniform distribution and strong bonding of BP inside the TPCS matrix at 10 wt.% demonstrate how the proper quantity of starch matrix substantially affects the uniformity and structure of starch-based films, which gain in tensile strength. It is widely known that plasticizers, like glycerol, improve the mechanical characteristics of starch-based matrices by increasing the flexibility and interaction of polymer chains, increasing tensile strength [36]. Plasticizers have the ability to reduce the brittleness of the starch matrix in TPCS/BP films, which facilitates better integration of BP fibres and improves the mechanical performance of biodegradable thin films overall [37]. Higher filler content has also been shown to cause phase separation and decreased interfacial adhesion, which can have an adverse impact on tensile strength [38]. Consequently, to get the desired mechanical performance, it is necessary to maintain an ideal balance between the matrix and filler concentration. BP concentration of 10 wt.% offers the optimal balance, resulting in increased tensile strength and the possibility for practical implementation in ecologically friendly materials.

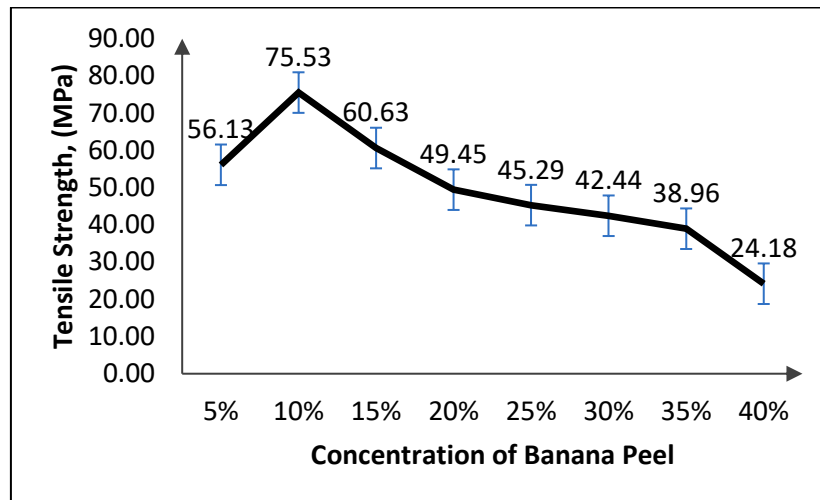


Figure 2. Tensile strength against concentration of banana peels

4.4. Tear Resistance Analysis

Figure 3 illustrates the tear resistance test results, showing that the specimen with a 10 wt.% concentration of banana peel (BP) had a maximum tear resistance of 50.78 N/mm. Adding BP at this concentration particularly strengthens the TPCS/BP biodegradable thin film due to the excellent dispersion and interaction between the BP fibres and the polymer matrix. The mechanical properties of natural fibre composites are significantly improved when fillers are evenly distributed and well-bonded within the matrix. However, the crystalline structure of PVA could significantly improve the mechanical properties of composite films by restricting crack growth and providing structural stability [39]. This enhancement is explained by the approach that PVA and BP fibres cooperate in the TPCS matrix to create a stronger, more cohesive film structure.

In addition, the method of film formation, including casting and drying processes, can impact tear resistance [40]. Uniform distribution of fillers is essential to avoid weak spots that can compromise the film's mechanical integrity. Weak spots in the film might decrease tear resistance because the banana peel (BP) fibres are not dispersed uniformly. Furthermore, interactions between the banana peel fibres and the thermoplastic corn starch (TPCS) matrix affect the film's ability to withstand tearing [41]. At ideal BP concentrations of 10%, these interactions enhance mechanical performance. At higher concentrations, such as 40 wt.%, the risk of filler agglomeration rises, which may result in weak regions in the film and reduced tear resistance. Thus, optimizing the filler content and ensuring homogeneous distribution within the polymer matrix are key strategies for improving the mechanical performance of biodegradable composites [42].

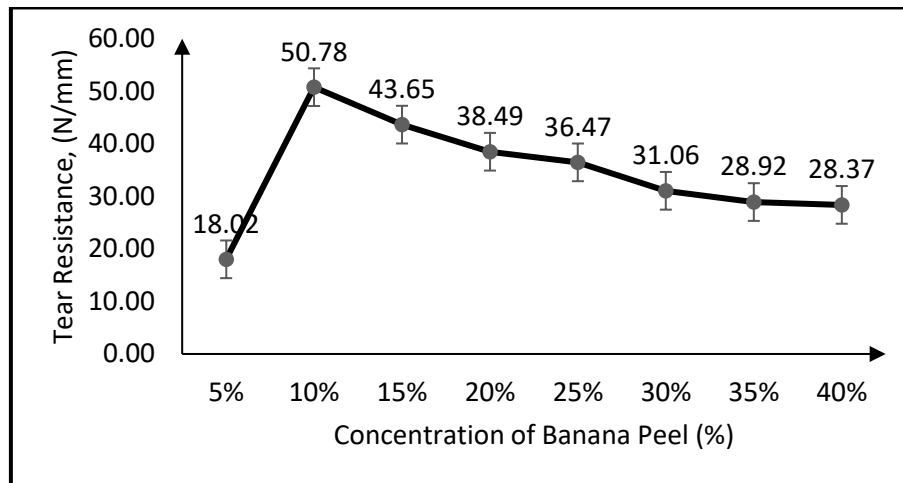


Figure 3. Tear resistance against concentrations of banana peels

4.5. Microstructure Analysis

SEM study of the film's surface morphology revealed structural alterations caused by the inclusion of banana peel extract. The images revealed a more homogenous extract distribution, which influenced the surface topography and may have improved functional qualities. Figure 4 shows the figure of surface morphology characteristic of thin films at different concentrations of BP extract (5 - 40 wt.%) at 250x magnification before the degradation test. The micrographs show that the fillers are dispersed consistently within the thermoplastic corn starch matrix. Embedding microcrystalline cellulose into matrix/polyvinyl alcohol films improved surface uniformity and decreased agglomeration, enhancing mechanical performance [43].

The findings indicate that incorporating BP extract correspondingly improved the surface uniformity of the TPCS/BP films. The reduction in agglomeration likely contributes to the films' increased mechanical strength and stability. The homogeneous distribution of BP extract within the matrix prevents the formation of weak spots that could compromise the film's integrity. Overall, the SEM analysis underscores the importance of proper filler distribution within the polymer matrix, which is essential for optimizing biodegradable thin films' mechanical and functional properties. It also helps to provide constant mechanical performance across the film because of the homogeneous distribution of BP extract [44]. This equal distribution contributes to the film's structural stability under different loads. Furthermore, enhanced surface homogeneity increases the film's appearance, making it more appropriate for commercial applications. The results reveal that optimizing filler dispersion is essential to creating high-performing biodegradable films [45].

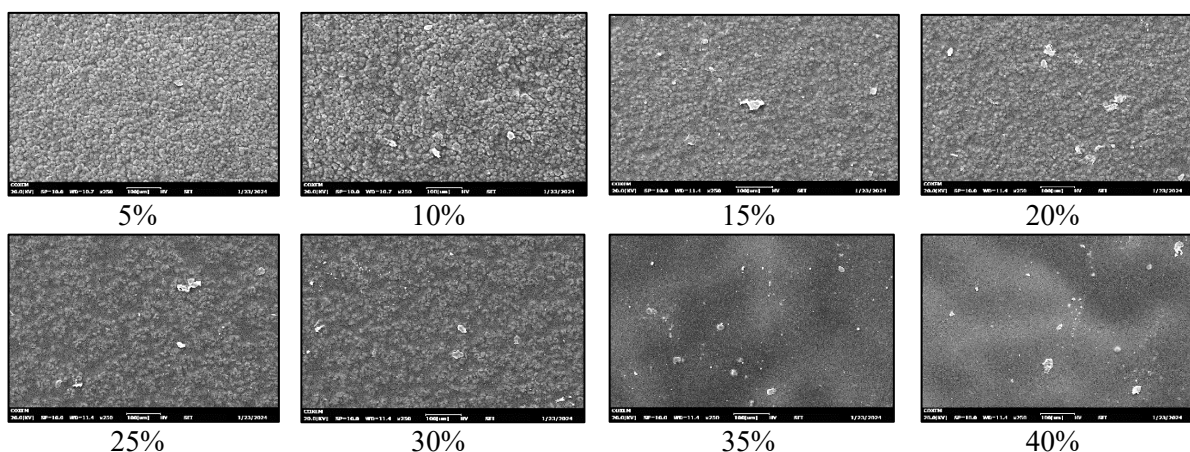


Figure 4. Surface morphology characteristic of TPCS/BP biodegradable thin film (Before)

Figure 5 shows that the samples significantly change the structure's surface. A sample with 5 wt.% of BP concentration content revealed a slight lack of uniformity on the surface sample even after eight weeks of biodegradation. However, sample TPCS/BP with 40 wt.% exhibited more surface irregularity, and the material also had a largely integrated structure with more cracks and ruptures. The degradation of the TPCS/BP biodegradable thin film in soil would include many microbial reactions, such as bacteria, fungi, and algae, with relatively time-required [46]. Microbial colonization and biofilm development further revealed that microbial activity played a role in speeding the degradation process [46][47]. This shows that increased BP concentrations may speed up the breakdown process, resulting in much greater structural disintegration.

The presence of microbial colonization and biofilm formation on the surface of the films further underscores the role of microbial activity in enhancing the degradation process. Microbial activity can significantly accelerate the biodegradation of biopolymers by breaking down polymer chains and facilitating the assimilation of degradation products. This microbial influence is crucial for the efficient biodegradation of TPCS/BP films, making them a promising alternative for sustainable packaging and other applications where environmental impact is a concern. Furthermore, the significance of microbial interactions in the biodegradation of biopolymer-based materials might reveal that microbial enzymes play a crucial role in dissolving the polymer matrix [49]. The structural changes observed in the TPCS/BP films with higher BP concentrations suggest that optimizing the filler content is essential for balancing mechanical integrity and biodegradability. This balance is crucial for producing biodegradable materials that may degrade in natural settings while maintaining useful qualities after usage. The accelerated degradation at greater concentrations of BP offers important information for creating biocomposite films with specific rates of degradation that meet particular application needs.

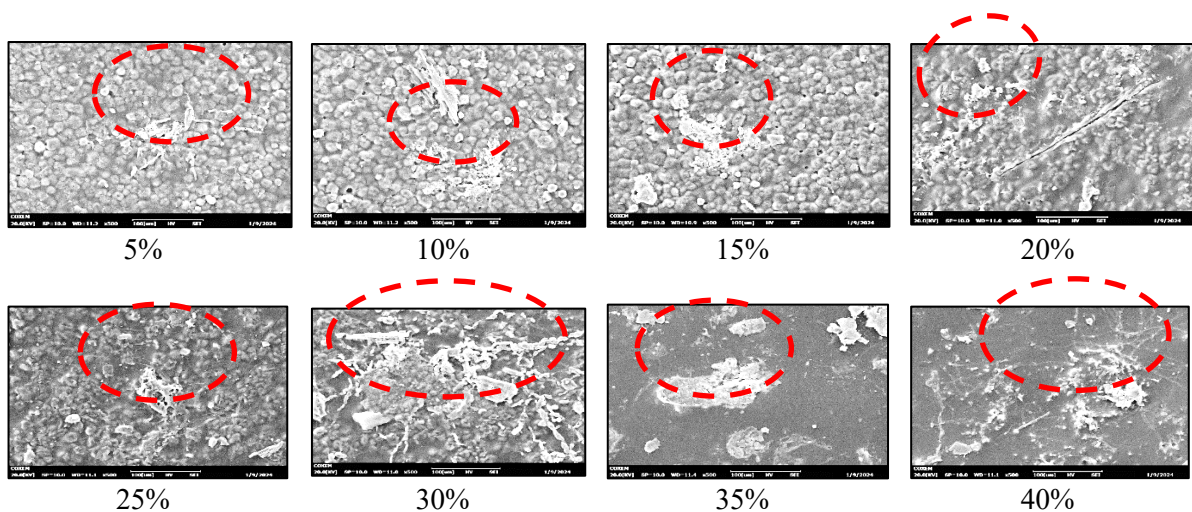


Figure 5. Surface morphology characteristic of TPCS/BP biodegradable thin film (After)

4.6. Weight Loss Analysis

The finding found that the percentage of the average weight loss shows the increment of the average weight loss as shown in Figure 6. The results show that the concentration of BP extraction content increased, leading to the percentage weight loss increment. The sample with the greatest concentration of BP extraction, 40 wt.%, had the largest average weight loss of 14.64%. This large weight loss suggests that the high BP concentration increases the biodegradation rate, probably because it increases the activity of microorganisms and the development of enzymes that quickly break down the polymer matrix [50]. The sample with the lowest BP concentration, 5 wt.%, had the smallest average weight loss at 5.32%, indicating that lower BP content leads to slower biodegradation rates. These findings highlight

the importance of BP concentration in regulating the biodegradation rate of TPCS/BP biodegradable thin films, hence offering an adjustable parameter for creating biodegradable materials.

Temperature fluctuations influence energy availability for chemical reactions and microbial activity, affecting the breakdown of biopolymer bonds. Warmer temperatures promote microbial metabolism and enzyme mobility, which accelerates up the disintegration of biopolymers. Humidity levels also impact water availability, and both parameters are crucial for microbial growth and the enzymatic reactions necessary for the degradation process [51]. Higher humidity promotes enzymatic activity by maintaining proper moisture levels, which facilitates the breakdown of biopolymer chains. On the other hand, dry conditions could inhibit the growth of microorganisms and the activity of enzymes, slowing the decomposition process. Furthermore, photochemical processes brought on by exposure to UV sunlight contribute to the breakdown of biopolymers by breaking down molecules and disrupting chemical bonds [51][52]. These environmental parameters impact the rate and amount of biopolymer degradation, highlighting the complex cooperation between the environment and material sustainability in various kinds of environments.

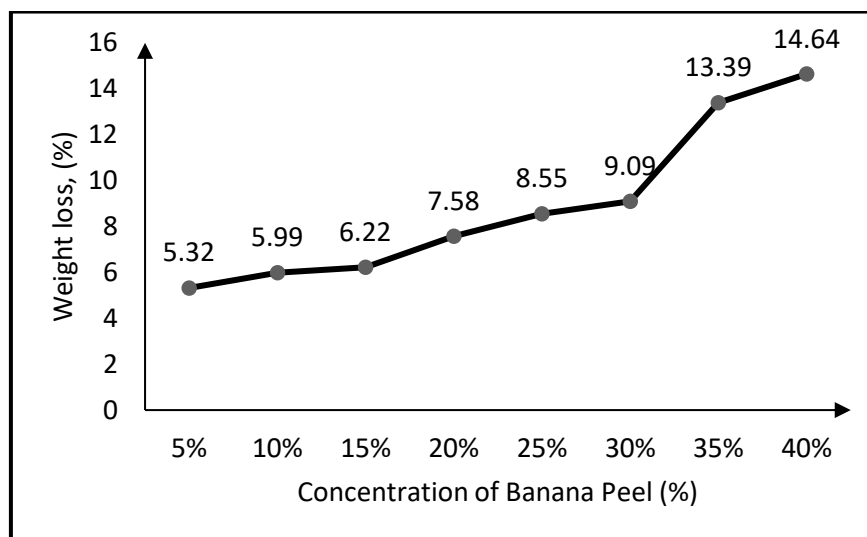


Figure 6. Average weight loss against concentration of banana peel

5. Conclusion

In conclusion, the development of banana peel as a reinforcement towards thermoplastic starch matrix to produce TPCS/BP biodegradable thin films has been successfully studied by identifying its physical, mechanical, and biodegradability properties. From the results, it is discovered that there is a high possibility that banana peels can be utilized to produce biodegradable thin film as it demonstrate promising physical, mechanical and biodegradability properties. The findings indicated that the moisture level of the BP powder was 91.31%. The 10 wt. (%) TPCS/BP biodegradable thin film showed the greatest tensile strength (75.53 MPa) and tear resistance (50.77 N/mm) among the various formulations. According to the biodegradable test, the material's density and porosity were 1.81 g/cm³ and 0.48%, respectively, and the breakdown rate was 5.99%. SEM analysis revealed that the surface grew more homogeneous as the TPCS/BP concentration increased. 40 wt. (%) TPCS/BP biodegradable thin film of the sample had a more homogenous distribution and a higher irregular surface compared to five percent, which had a little uniform surface.

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