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RESEARCH ARTICLE

Fourier-transform infrared spectroscopy, energy-dispersive X-ray, and physical characteristics of biodegradable plastics of banana peel (*Musa Paradisiaca*) mixed tapioca starch

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ABSTRACT - Bioplastics have become a subject of interest for numerous purposes, such as food packaging and biomedical applications. Synthetic plastic takes around 100 years to degrade due to its hydrophobic nature. The objective of this study was to identify the physical properties of thermoplastic starch (TPS)/ banana peel (BP) at eight different concentrations of banana peel (BP), namely 5 wt.%, 10 wt.%, 15 wt.%, 20 wt.%, 25 wt.%, 30 wt.%, 35 wt.% and 40 wt.%. BPs were cleaned, oven-dried at 70 °C, and ground into a particle size of 0.23 ± 0.02 mm. BP extract was obtained through the maceration process to develop eight different concentrations of TPS/BP. The bioplastic characteristics regarding physical properties were presented using FTIR analysis, SEM analysis, density, and porosity tests. The resulting FTIR spectra revealed a similar pattern. However, the peak at 2853.5 cm^{-1} revealed the presence of BP extracts with a slightly sharper spectrum. The 40 wt.% TPS/BP indicated uneven surface and the presence of predominant elements of Mg, Na, Ca, and Fe, with values of 1.04%, 7.82%, 14.10%, and 7.52%, respectively. The 0 wt. % TPS/BP showed the highest degradation rate of 1.89 g and density of 1.32 g/cm^3 But the lowest porosity of 0.09%. The TPS/BP biodegradable plastic has provided significant good physical properties to replace other synthetic polymers.

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1. INTRODUCTION

The municipal solid waste (MSW) generation level is directly linked to the regional economic development, industrialization rate, and public practices [1]. MSW consists of daily items, which include biodegradable and non-biodegradable materials, dangerous substances, or construction waste [2]. MSW is a significant concern in Malaysia, and the use of plastics significantly affects its composition. Improper plastic waste management and other types of MSW have negatively impacted the environment, such as pollution and habitat damage, particularly in coastal areas [3]. To resolve this issue, Malaysia has initiated the development of municipal trash management laws, which aim to reduce the consumption of commercial or synthetic plastics, promote recycling benefits, and encourage environmentally friendly waste disposal methods [4]. MSW in Malaysia is expected to increase from 2.4 billion tons to about 2.6 billion tons by 2025 due to escalated urbanization and income levels [5]. Food waste accounts for 40–50% of the wastage rate for food crops, roots, and vegetables. Approximately 65 kg of food is annually wasted per person, with vegetables accounting for 25%, cereals for 24%, and fruits for 12% of the total food waste [6]. Composting may considerably reduce the MSW directed to incineration facilities or landfills [7].

The improper disposal method of banana peels (BPs) in landfills contributes to environmental issues [8]. Bananas are abundant and can act as a renewable resource that helps reduce dependence on non-renewable petroleum-based products, promoting environmental sustainability. The fact that bananas grow all year round and everywhere in the world contributes to their abundant and easy availability. Bananas are the world's second most widely produced fruit, accounting for 16% of global fruit production [9]. Banana production in Malaysia was 330597 tonnes, valued at RM 552,697, making bananas the country's second-largest crop cultivated after durian [10]. It then demonstrates the significance of managing hazardous agricultural waste, including crop and fruit waste, which can effectively transform into biomaterials, such as biopolymers, biofuels, and biofibers [11]. Nevertheless, banana peelBPs contain high nutrients, such as carbohydrates, crude fibers, and proteins, which have benefits either in compost or soil. It is suitable for developing biodegradable plastic due to its characteristics, which cause it to degrade easily and rapidly in the environment and maintain warm and humid surroundings [12]. Moreover, plastic is in demand, especially in packaging, due to its numerous advantages, such as low-cost production, water resistance, rust resistance, flexibility, and durability [13]. Plastic waste accumulation in the environment drives the industry to create sustainable and biodegradable plastics. To build a green environment and prevent the possible dumping of stubborn plastic trash globally, the production of bioplastics has received substantial

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attention due to its biodegradability [14]. Bioplastics refer to bio-based plastics derived from biomass and renewable resources, such as polylactic acid (PLA) and polyhydroxyalkanoate (PHA), or to plastics derived from fossil fuel. For example, the use of starch as a renewable resource in the development of bioplastic packaging resulted in lower consumption of non-renewable energy resources (-50%) and thus lower greenhouse gas emissions (-60%) as opposed to polystyrene packaging [15-17]. Bioplastics, often known as biodegradable plastics, may break down completely or partially, reducing their adverse environmental effects. As a result, a plasticizer, a polymer additive in film blended with glycerol, is necessary to improve the film's mechanical and physical properties. This includes improving the films' biodegradability, strength, flexibility, and deterioration in soil conditions [18]. Starch contains high intermolecular interactions and hydrogen bonds, making it challenging to treat as a thermoplastic. However, these intermolecular interactions may be broken when starch is plasticized, which enables it to function like a thermoplastic material. Thus, plasticizers, such as urea, glycerol, and glycerin, are added to water to create a deformable thermoplastic substance known as thermoplastic starch (TPS), plasticizers, such as urea, glycerol, sorbitol, and glycerin, are added to water [19].

Natural starch is the best bio-based polymer that can replace plastic due to its biodegradable properties. Particularly, plant fibers offer advantages such as reduced energy and consumption during manufacturing, enhanced physical and mechanical properties, easy availability, and lightweight and low-cost products [20-22]. High consumption of bananas tends to generate abundant banana peels as waste, and uncertainly, it provides benefits in exploring more research about bioplastics and thermoplastic starch as potential alternatives to conventional plastics. Utilizing plastic polymer derived from BP waste leads to sustainable ability, reducing environmental impact and improving waste management effect. Indeed, strategic modifications and blends are feasible alternatives to manufacturers in providing technology potential in creating plastics with starch-based materials [23]. The Malaysian market has a notable demand for biodegradable plastic products, attributed to rising environmental awareness and sustainability concerns among customers. In addition, Malaysian consumers are willing to pay for premium biodegradable plastic items, indicating a large market potential for such products in the country [24]. Additionally, the laws and policies from the government promote the use of biodegradable plastics and play an important role in raising the demand for the products on the market even further [25]. The potential of biodegradable plastic packaging in multiple industries in Malaysia indicates the market's wide-ranging uses and opportunities. In Malaysia, biodegradable plastics offer a long-term approach to the environmental challenges of conventional plastics. Biodegradable plastics present a chance to reduce the environmental impact of plastic waste, alongside the country's growing awareness of environmental conservation and the urgent need to control plastic pollution [26].

Biodegradable plastic is currently developed as a sustainable alternative to conventional synthetic plastic. Agricultural films or grow bags, packaging, and disposable catering supplies are some of the main markets for developing biodegradable plastics. Its ability to quickly break down and decompose into the environment promotes the growth of biodegradable plastic [27]. Biodegradable plastics can have fewer negative impacts. As the environment is associated with climatic changes, attaining a sustainable environment for future generations has become a national and international challenge [28]. It provides lower production costs, rapidly disintegrates, and can be utilized as fertilizer [29-30]. Biodegradable plastic breaks down more quickly than petroleum-based plastic, which boosts its potential as an alternative material due to its biodegradable qualities. Natural fibers have numerous benefits, such as abundant, cost-effective production, adequate strength, low energy use, and lightweight [31]. Natural fibers have recently gained attention due to their degradable properties without causing harmful effects on the environment. They are categorized as renewable resources such as plant, animal, or mineral fibers. Plant fibers comprise fruit, seed, leaf, or plant parts [32-33]. Starch is the most promising bio-based polymer, and it is considered suitable for many industrial applications since it is biodegradable, widely available, non-toxic, and presents a competitive price. In addition, starch can be processed into a thermoplastic-like material in the presence of heat, shear, and plasticizer, which improves some of the features of native starch and its processability [34]. It is necessary to consider the limitations to identify thermoplastic suitable for a particular purpose. Its performance can be enhanced through material decision-making, processing methods, and additives. Thermoplastic is plastic polymers that can be melted and softened by applying heat [35]. Nevertheless, thermoplastic starch (TPS) has poor mechanical characteristics in terms of low tensile strength and density and a limited range of compatibility. However, despite these disadvantages, TPS is broadly used in packaging, food, and agricultural films due to its affordable price, ability to degrade, and ease of regenerative processes [36]. TPS also has boundaries that prohibit their broad applicability regarding physical and mechanical properties. Banana fibers are added to thermoplastics to improve the mechanical properties, such as modulus, tensile strength, and impact resistance. Chhatariya et al. [37] found that adding orange peel powder (OPP) by 0 - 40% with corn starch as filler increased tensile strength from 18.70 MPa to 24.32 MPa. Reza et al. [38] studied the blend composition consisting of 10% glycerol, 75% water, and 15% cornstarch, where the mechanical strength and functionality decreased as the composition exceeded 60–70%. Verma et al. [39] found that 2.0% w/w starch exhibited the highest degradation of 70% as the reinforcement of banana peel paste (BPP). In addition, Saepoo et al. [40] found a fractured surface seeding pot at 0 wt. % oil palm mesocarp powder (MPC), revealing a smooth and homogenous structure. In contrast, 50 wt% MPC showed the strongest network between fiber-starch interfacial adhesion as the fibers were well distributed, but the biodegradability properties declined. The particle size influenced the thickness of the starch film as large-particle size cassava starch/bagasse with higher concentration indicated the lowest density value of $1.10\ g/cm^3$and the highest starch film thickness of 0.49 mm [41].

The selection of materials in this research was based on the material availability, low production cost, and use of organic waste material to produce a valuable product. Using BPs as filler material could boost specific properties of the value-added product. Additionally, applying natural filler to the composite material provides substantial environmental benefits, such as biodegradability, low density, relatively low cost, improved durability and energy recovery, reduced emissions of contaminants, and reduced consumption of non-renewable sources [42]. Thus, this research can contribute to environmental friendliness to avoid BPs from rotting as it can cause environmental issues. This research also focused on the characterization of TPS reinforced with BPs. The results of this study should be beneficial for future research and the bio-based plastics industry in making decisions about using natural resources to make biodegradable thin films.

2. MATERIALS AND METHODS

2.1 Preparation of Banana Peels as Filler

The fabrication method of biodegradable plastic requires several steps, including drying, grinding, extracting BPs, and blending into polymer matrix composites. The BPs were obtained from the small banana crips industry in Pekan Panchor, Muar, Johor, Malaysia. Fresh fruit peels usually have high moisture content, which affects their shelf-life. Hence, BPs must be preserved to maximize their shelf-life. To date, drying has been the standard approach for maintaining food and bioproducts by evaporating water through mass and heat transfer from the material. Heat energy is transmitted into the material to provide energy for water evaporation. This will reduce the material's mass due to the removal of moisture from the substance to the atmosphere [43]. Figure 1 shows the raw BPs cut into small pieces to the size of 2.0 ± 0.5 cm (length × width), and each part of BPs was cleaned with water before oven drying. The peels were dried in the convection oven at 70 °C for 24 hours.

(a) (b) (c)

Figure 1. Drying process step: (a) BPs were cut into small pieces, (b) BPs were placed in the oven, and (c) Oven-dried BPs

To achieve maximum extraction yield, BPs were ground into powder. Smaller particle size provides higher surface area [44]. Dried BPs were ground to a diameter range of 0.23 ± 0.02 mm using a high-speed grinding machine. Figure 2 shows the grinding process of BPs at 3450 rpm, 220-240V, and 0.3 mm. The ground BPs were sieved using a sieve shaker with a mesh size of 212 μm to obtain BP particles in the 0.23 ± 0.02 mm range.

(a) (b) (c)

Figure 2. Grinding process: (a) Grinding machine, (b) Dried BPs in powder form, and (c) Sieving process

As seen in Figure 3, the maceration process with slight alterations was conducted to extract ground BPs. The maceration of natural fillers involves soaking the filler in the solvent at room temperature to extract bioactive components, which are subsequently integrated into biodegradable films for active packaging applications [45]. In this study, BP powder was macerated for 24 hours at a ratio of 1:10 in ethanol, a frequently used extraction solvent. To fabricate biodegradable plastics, the BP extract was separated into eight sets of varying concentration, namely 5 wt.%, 10 wt.%, 15 wt.%, 20 wt.%, 25 wt.%, 30 wt.%, 35 wt.% and 40 wt.%. As indicated in Table 1, eight biodegradable plastic samples were produced with varying thermoplastic starch compositions as the polymer matrix and BPs as the filler.

(a) (b) (c)

Figure 3. Extraction process: (a) weighing BP powder, (b) ethanol with 99 % purity, and (c) maceration method for extraction

Table 1. Composition of TPS/BP

Types of Samples	Natural Fiber	Thermoplastic		
	Extraction of Banana Peel wt. (%)	Tapioca Starch wt. (%)	Glycerol wt. (%)	Distilled Water wt. (%)
A	5	5	1.5	88.5
B	10	5	1.5	83.5
C	15	5	1.5	78.5
D	20	5	1.5	73.5
E	25	5	1.5	68.5
F	30	5	1.5	63.5
G	35	5	1.5	58.5
H	40	5	1.5	53.5

2.2 Preparation of TPS as Polymer Matrix

Figure 4 demonstrates preparing TPS as a matrix or binder to fabricate biodegradable plastics. The TPS was developed using a combination of 5 g of tapioca starch, 1.5 g of glycerol, and 88.5 g of distilled water. Tapioca starch was plasticized with glycerol to create the matrix, and distilled water was added to the solution. As the mixture reached 45 °C, it was slowly stirred with a spatula for 30 minutes to ensure all solutions were homogenized until there were no visible lumps or bubbles.

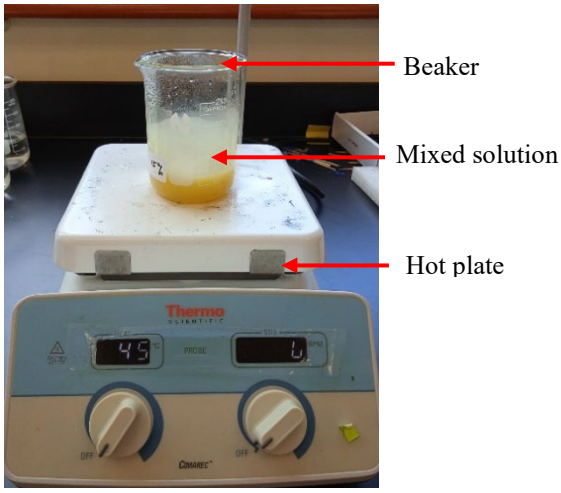


Figure 4. Thermoplastic starch

2.3 Preparation of TPS/BP Biodegradable Thin Film Samples

This study employed the hand lay-up method. It is the most popular and least expensive form of open molding as it involves the least amount of equipment needed. Eight samples with varying compositions of 5 – 40 wt.% became the basis for preparing the TPS matrix, as indicated in Table 1. Subsequently, the blend was manually poured into a mold

with a dimension of 20 cm x 15 cm. Figure 5 illustrates the fabrication process of TPS/BP, which was dried and hardened for 48 hours at room temperature. After the samples were cured, they were de-molded, and the thickness of each sample was measured and recorded using a Vernier calliper. The physical properties of TPS/BP samples were determined.

Figure 5. TPS/BP biodegradable plastic polymer

2.4 Particle Size Determination

At the Material Science Laboratory, UTHM, the Olympus Metallographic Microscope model (BX53M/BXFM, Japan) and Image Analysis software were used to measure the particle size of the ground BPs. The measurement was conducted according to ASTM D6913 [46]. The measurements were taken at different places at 5X magnification to acquire more precise readings.

2.5 Thickness Determination

The thickness of the TPS/BP polymer composite was measured using Clarke CM145 hand-held electronic digital vernier caliper according to ASTM D5947 standards [47]. Measurements were taken at five random positions on each film, and the average values were calculated to ensure accuracy and consistency in the thickness of each TPS/BP biodegradable plastic film sample.

2.6 Fourier Transform Infrared Determination

Fourier transform infrared (FTIR) analysis was conducted under ASTM 5477-18 [48]. The TPS/BP thin film samples (5-40 wt. %) were placed in the FTIR spectrometer to begin the analysis. This equipment emits light on the sample and measures the frequency at which it absorbs infrared light. The sample must be sufficiently thin to permit the infrared light to pass through it. Spectra from a broad spectrum of samples are then collected and stored in the reference database for accessible recognition and comparison during analysis. FTIR analysis uses interferometry to discover more about the substance found within the infrared beam. This method facilitated the analysis of the thin film samples and enabled the derivation of important insights regarding characteristics and uses.

2.7 SEM and EDX Determination

Solid inorganic material microanalysis and failure analysis are two frequent scanning electron microscope (SEM) applications. The standard manual for quantitative analysis using energy-dispersive X-ray (EDX) spectroscopy is ASTM E1508-12a [49]. Each sample of TPS/BP (5-40 wt.%) was cut into sizes of 0.5 cm x 0.5 cm and inserted into the focused beam of high-energy electrons, employed in SEM to extract various signals from specimen surfaces. Data from a specific area of the specimen surface are acquired during SEM examination, enabling information about its chemical compositions, crystalline structure, and crystal orientations to be obtained. This method allows for an in-depth examination of the quality and attributes of the materials, and it is beneficial for qualitative or semi-quantitative evaluations.

2.8 Mass

The mass of eight samples with different concentrations of BPs was measured according to ASTM E898-20 [50]. An analytical balance was employed to measure the mass of the sample. A biodegradable plastic sample was placed on the analytical balance to obtain its mass. The reading of mass was observed until it became constant. Then, the constant value was recorded.

2.9 Density

The ASTM D792-13 [51] standard test was followed to measure density. The sample was submerged in a weighing container to determine its weight. After that, the Mettler Toledo printer printed the data after determining the sample density. The sample was then removed with pliers, wrapped in filter paper to remove any remaining water, and placed on the weighing pan in the air to determine the wet weight of the sample. Equation 1 was used to calculate the sample density.

$$\rho = \frac{A}{A-B}(\rho_o - \rho_L) + \rho_L \quad (1)$$

where, ρ is the density of the sample, A is the weight of the sample in air, B is the weight of the sample in the auxiliary liquid, ρ_0 is the density of the auxiliary liquid and ρ_L is the density of air

2.10 Porosity

Porosity measurement was carried out according to ASTM D2734-16 [52]. Eight biodegradable plastic samples with different concentrations of extracted BPs were prepared. Each of the samples was then subjected to the microscope separately. Using the Image Analysis software, an image was captured for analysis purposes.

3. RESULTS AND DISCUSSION

3.1 Size Particles of Ground Banana Peel

The average area of BP particles determined from 10 places was analyzed to acquire accurate measurements. The average area of BP particles was 0.05 mm² in ten areas, with a particle size range of 0.01 – 0.12 mm². The particle size analysis of BP using an optical microscope is shown in Figure 6. Since particle size can impact material properties, processing, and end-use performance, its analysis is essential for powders, nanoparticles, and composite materials [53]. Moreover, smaller particles disperse more evenly, reduce agglomeration, and increase thermal resistance, which is critical in temperature-sensitive applications.

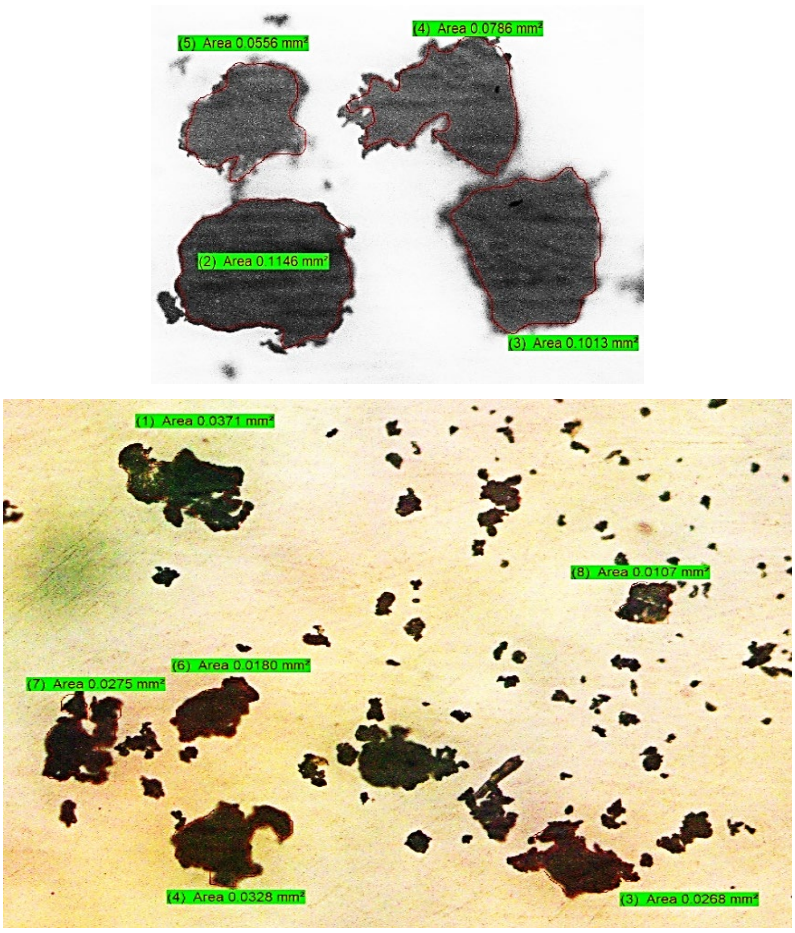


Figure 6. Optical microscope image of ground BP

3.2 FTIR Analysis

FTIR spectrophotometer was used to characterize the TPS/BP thin film sample. Figure 7 demonstrates the FTIR spectra of all samples with similar wavelength patterns. Peak at 3294.87 cm^{-1} represents the stretching vibration of hydroxyl (-OH) groups caused by the complex vibrational stretching in carbohydrate structures. However, from 1320 to 1380 cm^{-1}, it represents CH_2 bending vibrations in the TPS/BP biodegradable plastic film [54]. The peaks at 2920.31 cm^{-1} and 2853.5 cm^{-1} also indicated the existence of CH_2 groups within the starch structure and differences in the amylose and amylopectin ratios in the BP powder. The results revealed the presence of BP extract in all samples as

the peaks in the spectrum at 2853.5 cm^{-1} became sharper. The peaks between 1590 cm^{-1} and 1720 cm^{-1} in the spectra could be associated with the bending mechanism of hydroxyl groups in water molecules, resulting in the deflection of -OH group water. The peaks at 1423 cm^{-1} indicated O-H bending. The absorption band stretching from 480 to 410 cm^{-1} at lower wavenumbers revealed the stretching and bending of C=C and =C-H, respectively. This pattern facilitated the identification and comparison of the sample with the reference spectrum of various types of hydrogen bonding interactions produced by the soluble polymer, which causes the FTIR spectrum to shift and widen [55].

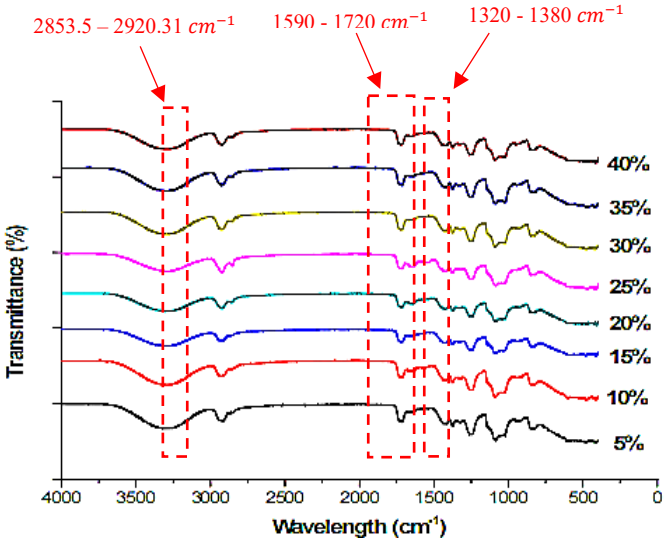


Figure 7. FTIR spectrum of biodegradable plastics

3.3 SEM and EDX Analysis

Table 2 displays the surface morphology of the TPS/BP samples with different percentages of BPs analyzed by SEM 50X magnification. Based on the morphological images, the fillers were evenly distributed throughout the TPS matrix, producing polymers with comparatively smooth surfaces and few inconsistencies [56]. However, when the filler content increased, numerous irregular distributions of filler aggregates appeared inside the TPS matrix. It is most likely because the starch blob does not entirely dissolve during the heating and stirring of the filler and starch matrix [57]. The micrographs of the sample with 40% BPs revealed a more uneven surface than those with the least BP content. Non-homogeneous morphological structure or insoluble starch in the organic solvent shows an irregularity due to the disturbance during the casting process [58]. In addition, EDX analysis was performed on the bioplastic samples to determine the elements present in the film. Table 2 shows the EDX spectra of bioplastics with different BP compositions of 5-40 wt.% at 500X magnification. The spectra of all films revealed the presence of high carbon and oxygen contents together with various elements, representing the structures of the polymer matrix and reinforcing material [59].

Other elements detected were silicon (Si), magnesium (Mg), iron (Fe), titanium (Ti), aluminium (Al), and potassium (K). Small amounts of calcium (Ca) and sodium (Na) were also detected in the spectra of the composites as a result of the chemical treatment used during the extraction of BPs. In addition, EDX analysis also proved the presence of minerals from BPs (K, Na, Ca, Fe, Mg), where the higher the concentration of BPs, the higher the respective mineral content. The lowest weight percentages of Mg (6.58%) and Na (1.18%) were found in the TPS/BP composite with 5 wt-% BP. TPS/BP composites with 40% BP exhibited the greatest weight percentages of Mg, Na, Ca, and Fe at 1.04%, 7.82%, 14.10% and 7.52%, respectively.

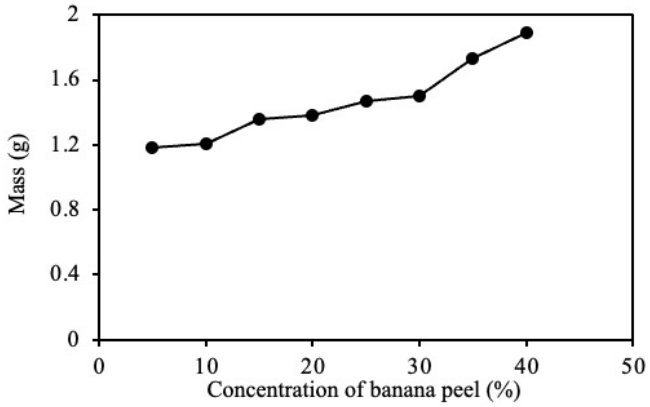
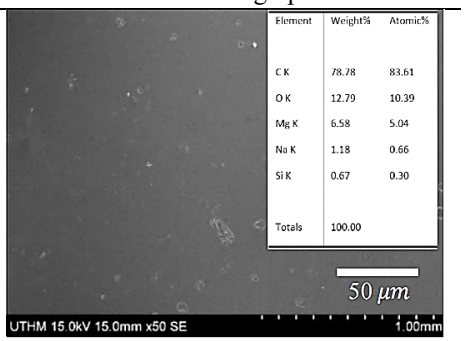
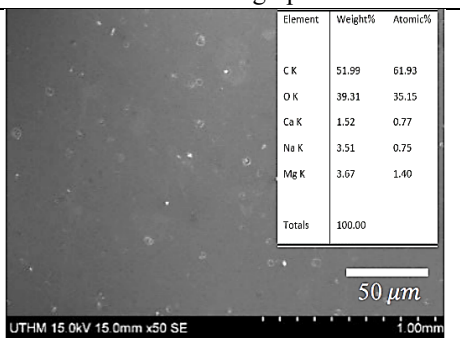
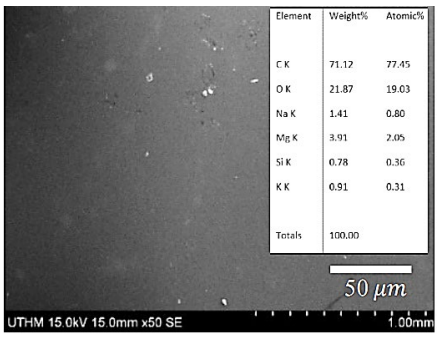
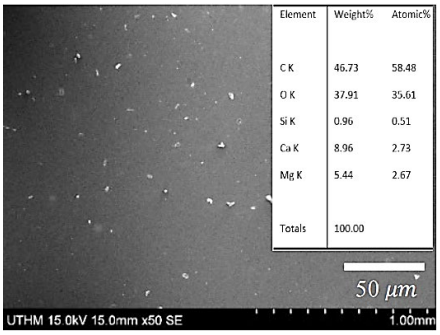
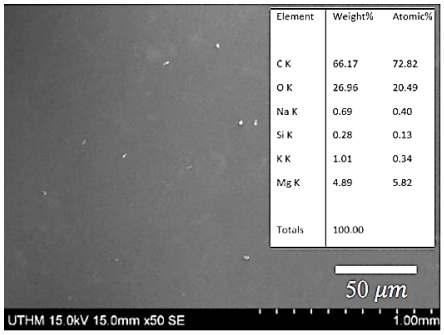
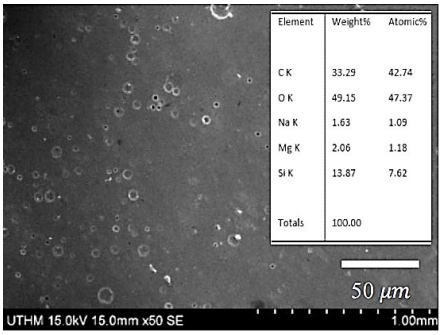
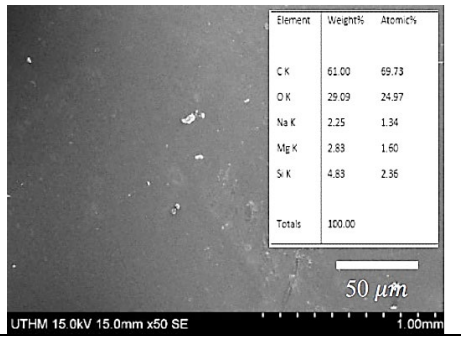
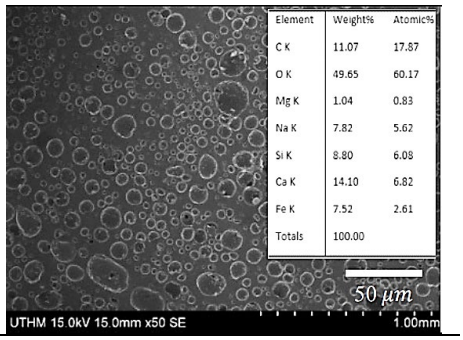


Figure 8. Mass against the concentration of BPs

3.4 Mass

Figure 8 shows the mass of biodegradable plastic samples against the concentration of BPs. Each sample was determined as mass average after weighing five times. The sample containing 40 wt.% BPs had the highest mass of 1.89 g, whereas the sample containing 5 wt.% BPs had the lowest mass of 1.18 g. It indicated that the mass of the biodegradable plastic samples increased as the concentration of the BP extract increased. The mass of the biodegradable plastic samples may change due to interactions between the BPs and the polymer matrix. The compatibility of the BPs with different polymer matrices and proper blending and processing methods could improve the interaction between the filler and matrix, imparting the composite materials more mass and better mechanical properties [60]. Indeed, BPs contained sizable amounts of cellulose and hemicellulose, which increased the mass of the plastic samples when added to the matrix.

Table 2. SEM micrographs and EDX analysis of TPS/BP samples

Samples	SEM Micrographs	Samples	SEM Micrographs
A		E	
B		F	
C		G	
D		H	

3.5 Density and Porosity

Figure 9 illustrates the density and porosity results of all samples with different concentrations of BPs. The higher density shown in the samples was caused by adding BPs as filler to the TPS. An increasing trend in density for all samples

was observed with the increasing BP contents. The sample with 40% BPs had the maximum density of 1.32 g/cm^3, whereas the sample with 5% BPs had the lowest density of 0.82 g/cm^3. Fillers are commonly added to increase the yield strength of the polymer, also known as the reinforcement effect. Polymers interact with the filler surface, forming an interphase layer at the particles' boundaries. The mechanical strength of the films may be increased by increasing the concentration of nanoparticles, which can result in higher density and reduced porosity [61]. Therefore, in this study, BPs, which acted as fillers, interacted with TPS to form an interface, subsequently forming a stronger bonding as the filler concentration increased. Moreover, an apparent decreasing trend in porosity was also discovered as the concentration of BPs increased. The analysis revealed that a sample with 5 wt.% BPs had the highest porosity value of 0.35%, while the sample with 40 had the lowest porosity value of 0.09%. Adding BP filler into the TPS decreased the porosity values of all samples. Previous research has shown that the efficiency of filler reinforcement is dependent mainly on many parameters, including the surface area size, dispersion degree, interactions between filler and polymer, and linkages among fillers. The filler surface may contain functional groups that prevent the filler from being directly integrated into the polymer matrix. Hence, the usual outcome is a slight increase in composite porosity due to the formation of filler agglomerates inside the hydrophobic polymer matrix [62].

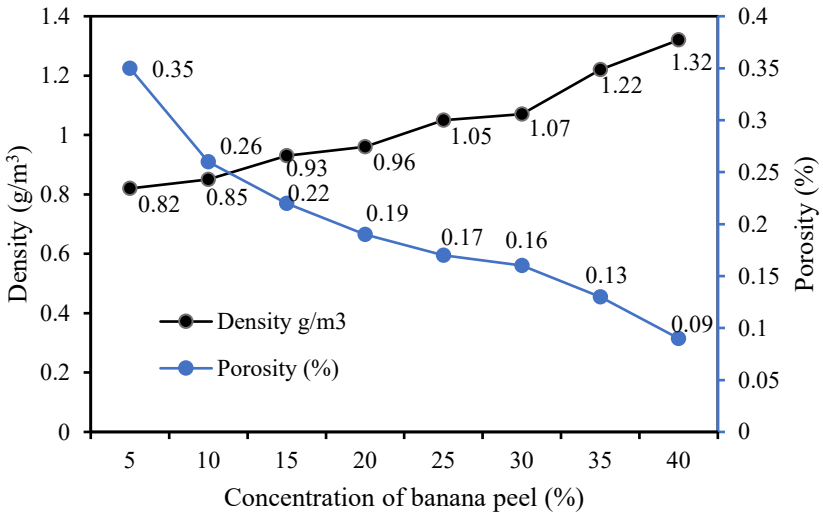


Figure 9. Density and porosity against concentration of BPs

4. CONCLUSIONS

In conclusion, utilizing BPs to reinforce TPS in fabricating bioplastic and its physical quality characterization were successfully investigated. It was possible to incorporate BPs into TPS to produce bioplastic based on their promising physical properties. At a peak of 2853.5 cm^{-1}, it revealed the presence of BP extract with a slight sharper of the FTIR spectrum. Next, the microstructure analysis of 40 wt.% BPs revealed a non-homogeneous and uneven surface, with the predominant presence of Mg, Na, Ca, and Fe at 1.04%, 7.82%, 14.10%, and 7.52%, respectively. Moreover, 40 wt.% TPS/BP recorded the highest mass of 1.89 g while 5 wt.% TPS/BP had the lowest mass of 1.18 g. The density values indicated that as the BP extract concentration increased, the density also increased. However, the porosity values decreased. A sample with 40% BPs exhibited the highest density value of 1.316 g/cm^3 among all samples. Meanwhile, the sample of 5% BPs displayed the highest porosity value, 0.351%. This research is significant as it improves the properties of bioplastic-containing BPs. Furthermore, the TPS/BP bioplastic outperformed commercial biodegradable plastic in terms of physical performance. Other types of organic waste could be studied for future work recommendations. The effect of different types of plasticizers on the physical and environmental properties of the bioplastics could also be investigated.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHORS CONTRIBUTION

M. Marsi (Project administration; Conceptualization; Formal analysis; Visualisation; Supervision)
I. A. Ariffin (Methodology; Data curation; Writing - original draft; Resources)
N. A. Huzaisham (Writing – review & editing)
A. Z. M. Rus (Validation; Investigation)
A. M. Said (Funding acquisition)

AVAILABILITY OF DATA AND MATERIALS

The data supporting this study's findings are available on request from the corresponding author.

ETHICS STATEMENT

Not applicable

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