Synthesis, Thermal, and Chemical Characterization of Durian Peel Starch-Based Bioplastic with Sorbitol Plasticizer and Chitosan or Zinc Oxide Filler Variations

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ABSTRACT

Plastic waste poses significant environmental challenges due to its persistence. Durian peel waste, which contains starch and lignocellulosic components, has potential as a renewable raw material for biodegradable bioplastics. This study aimed to evaluate the chemical characteristics and thermal stability of durian peel starch-based bioplastics containing chitosan or zinc oxide (ZnO) fillers at different tapioca starch–durian peel starch ratios. Bioplastics were prepared by blending and casting using tapioca starch and durian peel starch ratios of 1:1, 1:0.75, and 1:0.5, with sorbitol as a plasticizer and either chitosan or ZnO as fillers. Chemical characteristics were analyzed using FTIR, while TGA-DTA was used to evaluate thermal behavior. FTIR spectra showed the characteristic functional groups of the constituent materials, with no new absorption bands, indicating that the bioplastics were formed primarily through physical interactions and hydrogen bonding. Thermal analysis demonstrated that increasing durian peel content improved thermal stability. The highest residue yields were obtained for sample C, containing chitosan (22.976%), and sample F, containing ZnO (23.706%), at a tapioca starch-durian peel starch ratio of 1:0.5, indicating superior resistance to thermal degradation. The incorporation of durian peel lignocellulosic components together with chitosan or ZnO fillers enhanced the thermal stability of starch-based bioplastics. Among the formulations tested, the 1:0.5 tapioca starch–durian peel starch ratio exhibited the best thermal performance, demonstrating the potential of durian peel waste as a sustainable raw material for biodegradable packaging applications.

1. Introduction

Urban solid waste contains large amounts of non-biodegradable materials that persist in the environment and contribute to pollution. This challenge has increased interest in sustainable waste-management approaches and biodegradable alternatives to conventional plastics [1]. Plastic waste is a serious global problem due to long-term pollution. Plastic is very difficult to decompose, leading to decreased soil fertility, river siltation, marine animal deaths from ingestion or entanglement, and contamination of drinking water [2]. Unmanaged organic waste poses an environmental problem because it produces harmful greenhouse gases such as methane, contaminates soil and water sources, and can cause public health problems and damage infrastructure. Improperly disposed of organic waste can contribute to air and water pollution, affect public health, cause flooding, and increase the maintenance costs of infrastructure such as roads and water treatment facilities [3].

Bioplastics have been widely developed in several developed countries as an effort to address these problems. Bioplastics are derived from renewable resources, produced from agricultural or food-source materials such as starch, cellulose, and protein, and used for packaging and considered safe for food applications [4]. Durian fruit consists of 19-36% fruit flesh (aril), 4-17% seeds, and 50-70% fruit rind [5]. Durian peel waste, in addition to containing high levels of cellulose, is also rich in starch. The white part of the durian peel can be processed into starch flour containing 50% dietary fiber, 34.15% carbohydrates, 6.42% protein, and 0.38% fat [6]. Durian peel has therefore emerged as a promising feedstock for biodegradable materials and biocomposites, supporting both waste valorization and circular bioeconomy initiatives [6]. Previous studies demonstrated that durian peel fiber can enhance the thermal and mechanical properties of thermoplastic starch composites, indicating its potential as a reinforcing component in biodegradable packaging materials [7].

Several studies have shown that starch-based bioplastics require the addition of plasticizers and fillers to achieve strength and elasticity. Chitosan and ZnO serve as fillers in bioplastics. Fillers are needed to increase the strength of the bioplastic matrix [8]. Chitosan is additionally incorporated to enhance the transparency of the resulting bioplastic [9]. ZnO is a biocompatible material with starch that can act as a reinforcement of the bioplastics produced [10]. ZnO incorporation can improve thermal stability, residual mass, and reinforcement efficiency in starch biocomposites by restricting polymer chain mobility and promoting char formation during thermal degradation [11], [12]. The addition of fillers can result in rigid plastic that is easily broken, so plasticizers are needed. Plasticizers enhance the performance of bioplastics by penetrating starch granules and disrupting internal hydrogen bonds when exposed to elevated temperatures and shear forces [13]. Plasticizers are often used to improve elasticity and reduce barrier properties in starch films. As the amount of plasticizer increases, the material exhibits greater percent elongation [14]. Therefore, in this study, sorbitol, as a plasticizer, has the advantage of minimizing oxygen permeability and producing higher tensile strength values [8].

This study extends the work of Rahmatullah *et al.* [15] by providing a more systematic evaluation of durian peel-based starch bioplastics, with emphasis on the relationship between composition and thermal behavior. In contrast to previous studies, this work investigates the effect of varying tapioca starch-durian peel ratios. It compares the role of different fillers (chitosan and ZnO) on the chemical structure and thermal stability using combined FTIR and TGA-DTA analyses. No study has systematically compared chitosan vs. ZnO fillers in durian peel starch bioplastics across varying starch ratios. This study aims to evaluate the chemical characteristics and thermal stability of bioplastics prepared from tapioca starch–durian peel starch mixtures at different ratios, incorporating chitosan and ZnO fillers. FTIR was employed to investigate chemical interactions within the bioplastic matrix, while TGA-DTA was used to assess thermal degradation behavior and residual mass formation. It is hypothesized that higher durian peel content and ZnO filler enhance thermal stability through lignocellulosic reinforcement and the presence of heat-resistant inorganic particles. The findings provide insight into the structure–property relationships of durian peel-based bioplastics and support their development as sustainable, environmentally friendly packaging materials with improved thermal performance.

2. Research Methodology

The raw materials used in this study consisted of durian peel waste from Kuto Market, Palembang City, sorbitol as the plasticizer, and chitosan and ZnO as fillers. The bioplastic manufacturing process was divided into two stages: durian peel flour and bioplastic production. Chemical composition analysis was performed using Fourier Transform Infrared Spectroscopy (FTIR), and thermal stability testing was performed using Thermogravimetric Analysis-Differential Thermal Analysis (TGA-DTA).

2.1. Durian Peel Flour Production

The raw material preparation involved only the production of starch flour from the inner white portion of the durian peel, without delignification. The preparation process began by separating the inner and outer parts of the durian peel. The material used in this study was the inner white portion of the durian peel. The separated inner peel was then cut into small cube-like pieces and thoroughly washed under running water. Durian peel waste was prepared, then the white part was separated and cut into pieces approximately 5 cm in size. The next step was drying, initially sun-drying for 3 days, followed by oven-drying at 100°C until the material was dry and lightweight (constant weight). The dried durian peel was then ground using a chopper and blender to obtain coarse particles, and subsequently sieved using a 100-mesh sieve. From an initial mass of 7 kg of the white inner durian peel, approximately 240 g of durian peel powder/flour was obtained after the drying process.

2.2. Bioplastic Production

The bioplastic production procedure followed research by Melani *et al.* [16]. It began with the preparation of a 3-gram starch solution with a ratio of tapioca starch to durian peel starch (1:1; 1:0.75; 1:0.5) in 80 mL of distilled water, followed by the addition of 25% sorbitol plasticizer and 4% filler (chitosan, ZnO) of the total starch mass. The selected sorbitol concentration was based on previous studies demonstrating that 20–30wt% sorbitol effectively improves flexibility and processability while maintaining film integrity in starch-based bioplastics [8], [13]. Similarly, the filler concentration of 4 wt% was selected based on preliminary experiments and literature reports indicating that low filler loadings provide adequate reinforcement and dispersion without causing excessive particle agglomeration or brittleness [9], [10]. The selection of 4% filler was based on preliminary studies and literature, which identified this concentration as optimal for achieving good dispersion and desirable material properties. The bioplastic solution was then stirred and heated continuously for 10 minutes at 60°C. The final step was to mold the solution onto flexible glass and dry it in an oven at 45°C for 5 hours.

2.3. Bioplastic Characterization

The dried bioplastic films were carefully removed from the molds and characterized using Fourier Transform Infrared Spectroscopy (FTIR) and Thermogravimetric Analysis–Differential Thermal Analysis (TGA-DTA). FTIR analysis was performed to identify the functional groups and possible interactions among the bioplastic constituents. Spectra were recorded over a wavenumber range of 400-4000 cm^{-1} with a spectral resolution of 4 cm^{-1} and 32 accumulated scans for each sample. Thermal stability was evaluated using TGA-DTA. Approximately 5-10 mg of sample was heated from 30 to 600°C at a heating rate of 10°C min^{-1} under a nitrogen atmosphere with a flow rate of 50 mL min^{-1}. Weight loss, decomposition stages, and residual mass were recorded and analyzed to assess the thermal degradation behavior of the bioplastics.

3. Results and Discussion

3.1. TGA-DTA Test Results For Bioplastics

The thermal behavior of the bioplastic sample was evaluated using simultaneous thermogravimetric analysis (TGA) and differential thermal analysis (DTA), as shown in Fig. 1. Thermal stability analysis was conducted from 26-31°C, resulting in the TGA-DTA profiles shown. In these thermograms, the TGA curve (purple) and DTA curve (red) illustrate the progressive reduction in bioplastic mass, while the green curve represents the temperature-time relationship. As shown in Fig. 1, the TGA thermograms show mass loss with increasing temperature. In contrast, the corresponding heat flow during each phase of mass change is depicted in the DTA curves. The TGA curves in Fig. 1 show that the thermal degradation of the bioplastic occurs in multiple stages. The initial weight loss at lower temperatures is attributed to the evaporation of moisture and volatile components. The subsequent major weight loss corresponds to the decomposition of the polymer matrix, including starch and associated organic materials. At higher temperatures, the remaining mass represents residual char, likely influenced by inorganic components such as ZnO.

Although quantitative parameters such as the onset degradation temperature (T_0), maximum degradation temperature (T_{max}), and char yield were not determined, the observed weight-loss stages provide insight into the material's thermal behavior. The DTA curves support this interpretation, where endothermic transitions at lower temperatures are associated with moisture evaporation, while thermal events at higher temperatures correspond to polymer degradation. Overall, the thermal stability of the bioplastic is better understood based on its multi-stage degradation behavior rather than a single temperature value.

The TGA data indicate that all samples experienced a pronounced mass decline within a similar temperature interval, specifically from 110 to 460°C, followed by additional mass reduction up to 600°C. This degradation process occurs in two distinct stages, consistent with the two-step decomposition mechanism of starch-based bioplastics reported by Amin *et al.* [17]. The first stage, beginning around 110°C, corresponds to the release of bound water. At the same time, the initial mass reduction is attributed to moisture evaporation [18] and subsequent volatilization of the plasticizer, sorbitol, within the 125-290°C range [19]. The second stage, occurring near 460°C, involves the thermal breakdown of carbonaceous and hydrocarbon fragments derived from semi-crystalline starch components [12].

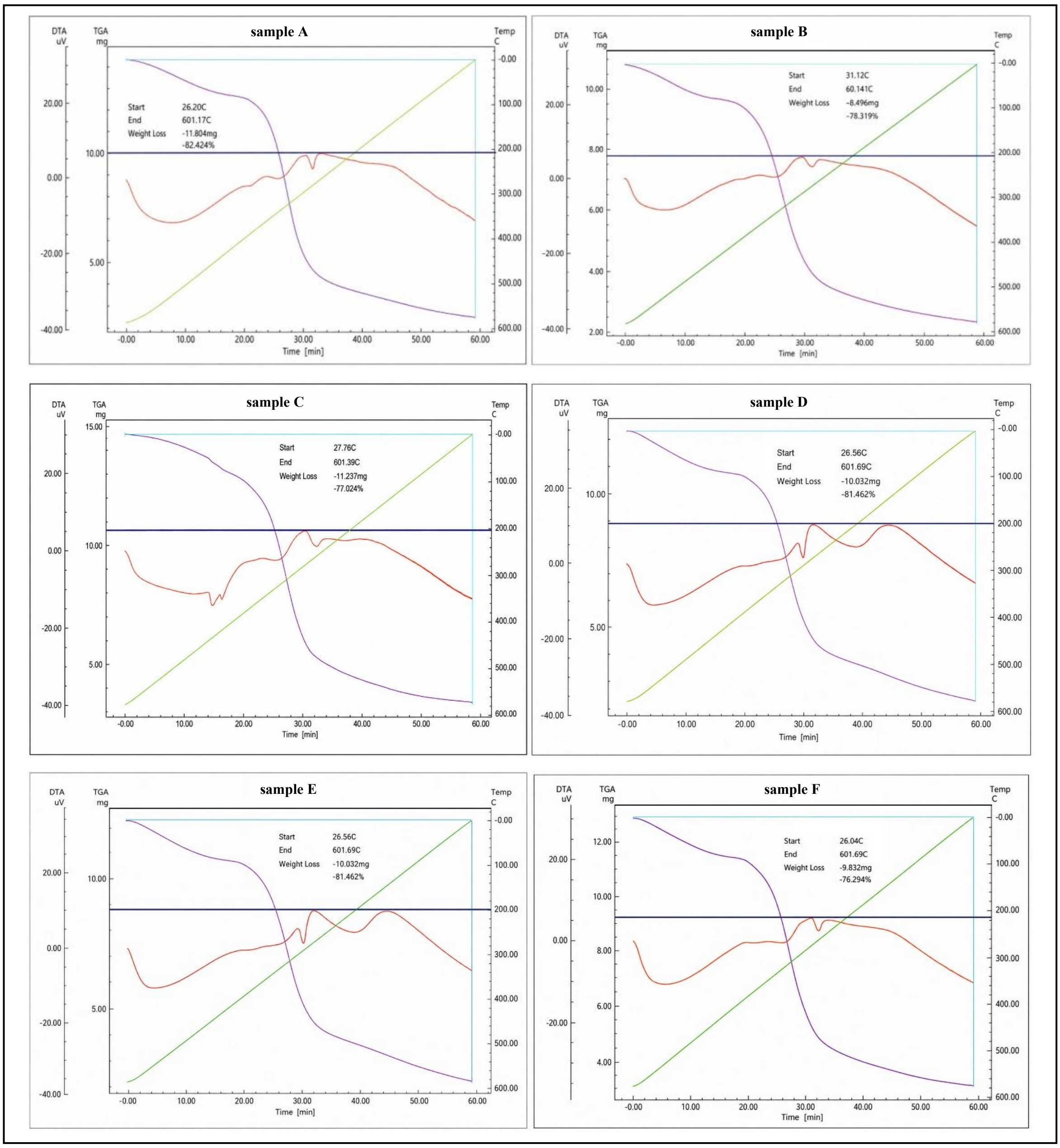

Fig. 1. TGA-DTA thermograms showing weight loss (TGA) and differential thermal analysis (DTA) curves of bioplastic from 3 grams of tapioca starch and durian peel for sample A (in a 1:1 ratio with chitosan filler), sample B (in a 1:0.75 ratio with chitosan filler), sample C (in a 1:0.5 ratio with chitosan filler), sample D (in a 1:1 ratio with ZnO filler), sample E (in a 1:0.75 ratio with ZnO filler), sample F (in a 1:0.5 ratio with ZnO filler)

The thermal profiles of samples A-C reflect multistep degradation behavior characteristic of starch-lignocellulosic composites, beginning with moisture loss, followed by substantial polymer decomposition associated with the depolymerization of starch and chitosan. The greatest mass loss corresponds to the exothermic degradation of cellulose, hemicellulose, and lignin originating from durian peel biomass. At the final degradation temperature of 600°C, sample A (initial mass: 14.321 mg) exhibited an 82.424% reduction in mass, sample B (13.256 mg initial mass) showed a 78.319% decrease, and sample C (14.589 mg initial mass) demonstrated a 77.024% total mass loss. Sample A

(1:1 tapioca starch to durian peel starch) displayed the highest total mass loss, while samples B and C exhibited higher thermal residue, indicating improved stability with increasing lignocellulosic content. Above 450°C, all samples gradually stabilized with final residues ranging from 17% to 23%. These results confirm that filler-rich formulations enhance thermal stability and char formation, consistent with previous reports on natural-fiber-reinforced bioplastics.

Thermal analysis of bioplastic samples D, E, and F with ZnO filler showed a similar thermal decomposition pattern, characterized by a gradual mass loss that increased with increasing heating temperature. Sample D, with an initial weight of 12,315 mg, experienced a mass loss of 10.032 mg (81.462%). Sample E, with an initial weight of 11,920 mg, experienced a mass loss of 10.032 mg, or 81.462%. Sample F, with an initial weight of 12,887 mg, experienced a mass loss of 9.832 mg, or 76.294%. The greater total mass loss in the sample with a higher starch content (sample D) confirms the role of the polysaccharide structure, which is more easily thermally degraded compared to samples with a higher filler content (samples E and F). The presence of ZnO as a filler improves the thermal stability of the bioplastic [20], as indicated by the shift of the decomposition onset to higher temperatures and a more stable DTA profile, which is consistent with the role of ZnO as a heat-resistant inorganic component. These findings suggest that adjusting the starch-to-durian peel ratio and adding ZnO can influence the thermal stability of the resulting bioplastic.

A comparison of the three ratios shows that the lower the proportion of tapioca starch and the higher the durian peel content, the greater the bioplastic's thermal stability. Sample D (1:1) experienced the greatest weight loss and was therefore most readily thermally degraded, while sample E (1:0.75) and especially sample F (1:0.5) showed a smaller mass loss and a more stable degradation pattern due to the contribution of the more heat-resistant lignocellulose from the durian peel. The presence of ZnO filler also improved thermal stability in all samples, but the effect was most pronounced in the formulation with a higher durian peel content.

Consistent with similar research, at 280°C, the main degradation stage in bioplastics is the glass transition, in which the solid, rigid bioplastic changes to a soft, elastic state. High temperatures influence this change. At 300°C, depolymerization occurs, the process of breaking the polymer chains in the bioplastic, resulting in a decrease in its weight. At 370-600°C, the solid bioplastic melts, changing to a liquid state. Although significant degradation occurs at higher temperatures (around 210 °C), initial mass loss begins at lower temperatures; therefore, the thermal stability of the bioplastic is better characterized by its multi-stage degradation behavior rather than by a single temperature threshold. However, at temperatures above 210°C, the bioplastic will degrade [21]. The thermal analysis indicated that adding both chitosan and ZnO fillers increased the residue yield. For the chitosan filler, the highest residue yield was observed in sample C at 22.976%, and for ZnO in sample F at 23.706%. Although these values are lower than those reported by Prasetyo *et al*. [21] (30.81%), this difference may be attributed to variations in raw material composition and filler content. The lower residue in this study indicates a higher proportion of biodegradable organic components, which may be beneficial depending on the intended application.

The thermal analysis indicated that adding both chitosan and ZnO fillers increased the residue yield. Studies on cassava starch bioplastics have reported residue yields ranging from approximately 20% to 31%, depending on the starch composition, plasticizer content, and reinforcing filler used [22]. Similarly, starch-based composites derived from arrowroot and potato starch have shown increased residual mass when reinforced with inorganic nanoparticles, indicating improved resistance to thermal degradation [11], [23]. The differences in residue yield among studies may be attributed to variations in starch source, lignocellulosic content, filler concentration, and processing conditions, all of which influence char formation during thermal decomposition.

A comparison of the fillers used in this study showed that ZnO yielded a slightly higher residue yield (23.706%) than chitosan (22.976%). This behavior is primarily related to the different thermal characteristics of inorganic and organic fillers. ZnO is a thermally stable inorganic metal oxide that does not decompose within the temperature range used in TGA analysis and therefore contributes directly to the residual mass after degradation. In addition, ZnO can act as a reinforcing phase that restricts polymer chain mobility and delays the thermal decomposition of the starch matrix. In contrast, chitosan is an organic polysaccharide that undergoes thermal degradation at elevated temperatures. However, it can enhance thermal stability through hydrogen bonding and improved intermolecular interactions within the polymer network. Consequently, while both fillers improved the thermal resistance of the bioplastics, ZnO exhibited a greater ability to increase residue yield and thermal stability. These findings are consistent with previous reports demonstrating that inorganic nanoparticle fillers generally provide superior thermal reinforcement compared with organic fillers in starch-based bioplastic systems [24].

3.2. Bioplastic FTIR Test Results

FTIR analysis is performed to determine the functional groups present in a polymer material, specifically a bioplastic in this context. In the chemical composition test, which identifies the functional groups of each bioplastic component, two representative samples were taken for each plasticizer type. Sample C was for chitosan, and sample F was for ZnO.

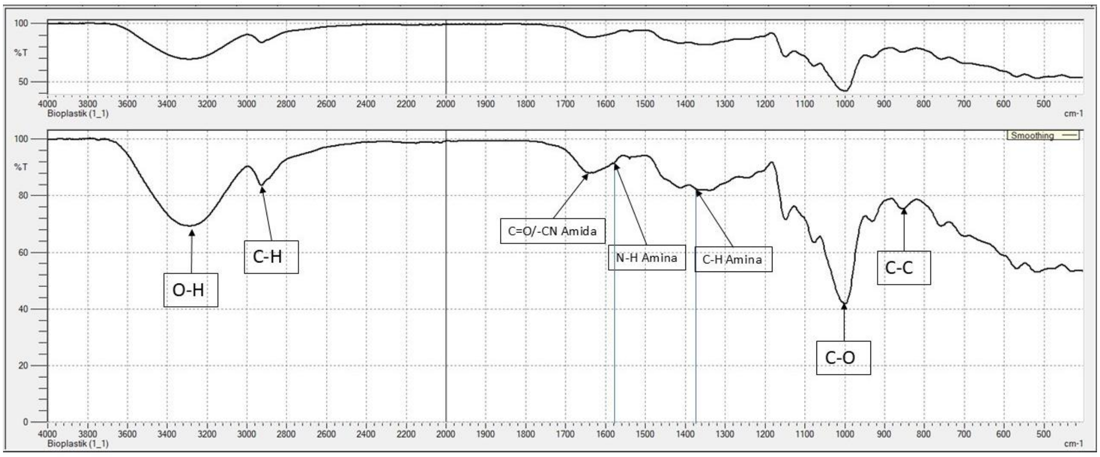

Fig. 2. FTIR test results for sample C (3 grams of 1:0.5 tapioca starch and durian peel with chitosan filler).

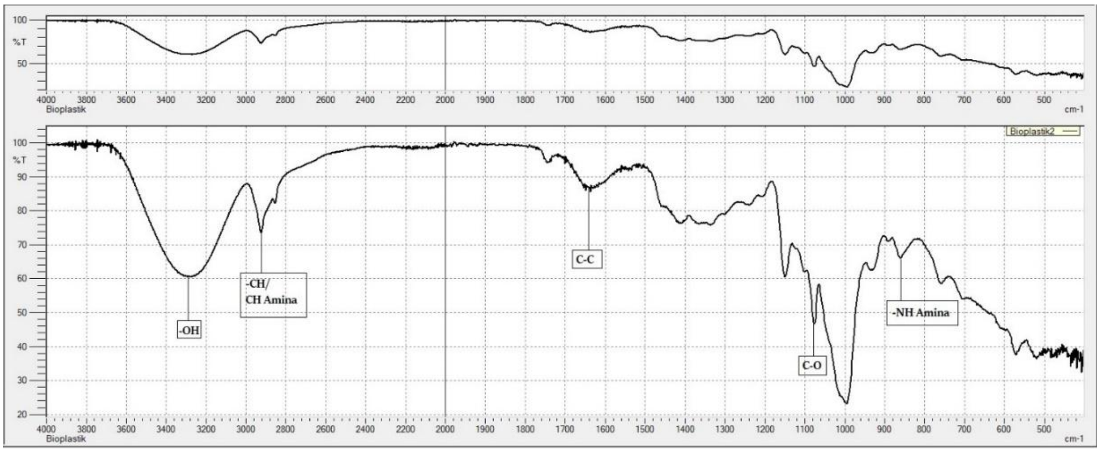

Fig. 3. FTIR test results for sample F (3 grams of 1:0.5 tapioca starch and durian peel with ZnO filler).

Based on Fig. 2, Fig. 3, and Tables 1 and 2, the FTIR spectra of durian peel starch bioplastics are shown. The FTIR spectra indicate that the bioplastic matrix is stabilized predominantly through hydrogen bonding and other intermolecular interactions rather than through the formation of new covalent bonds. However, this does not exclude the presence of physical interactions. The broad absorption band in the range of 3400-3460 cm^{-1}, corresponding to overlapping O–H and N–H stretching vibrations, indicates the formation of hydrogen bonding between starch, chitosan, sorbitol, and ZnO. Additionally, slight shifts in characteristic peaks (such as O–H/N–H, C=O, and amide bands) compared to literature values suggest intermolecular interactions within the bioplastic matrix. Therefore, the bioplastic structure is formed predominantly through physical mixing, accompanied by hydrogen bonding and other intermolecular interactions, rather than through chemical reactions [25].

A broad absorption band was observed in the region of 3200-3500 cm^{-1} for both samples C and F, corresponding to overlapping O–H and N–H stretching vibrations. The broadening of this band indicates extensive hydrogen bonding among hydroxyl groups from starch and sorbitol, amino groups from chitosan, and hydroxyl-containing components of the durian peel. In sample C, the O–H/N–H stretching band appeared at 3447 cm^{-1}, while in sample F it was detected at 3290 cm^{-1}. The shift toward lower wavenumbers in sample F suggests stronger intermolecular interactions, which are commonly associated with enhanced hydrogen bonding within the polymer network.

Table 1. Characteristic FTIR absorption bands of individual bioplastic components are reported in the literature

Component	**Wavenumber (cm^{-1})**								
	–OH	***–CH***	***C=O/ –CN Amide***	***NH Amine***	***CH Amine***	***–OH/ NH$_2$***	***C–O***	***C–C***	***Ref.***
Starch	3388	2929	–	–	–	–	–	1649	[25]
Sorbitol	3257	2937	–	–	–	–	–	–	[25]
Chitosan	–	2928	1654	1570	1381	3452	1033	894	[26]
ZnO	2925	–	–	889	2853	–	1026	–	[27], [28]

Table 2. FTIR absorption bands observed in durian peel starch bioplastics

Sample	**Wavenumber (cm^{-1})**							
	–OH	***–CH***	***C=O/ –CN Amide***	***NH Amine***	***CH Amine***	***–OH/ NH$_2$***	***C–O***	***C–C***
C (Chitosan filler, 1:0.5)	3259	2926	1659	1597	1375	3447	1007	895
F (ZnO filler, 1:0.5)	3290	2923	-	861	2923	–	1076	1647

The bioplastic peak at 3645.46 cm^{-1} corresponds to the O-H group of the zinc oxide filler and plasticizer [29]. Sample F shows a wavelength close to this value, at 3290 cm^{-1}. Based on research by Steven *et al.* [29] on chitosan-based bioplastic films, the FTIR results show that the wavelengths for functional groups are, respectively, 3452 cm^{-1}, representing the stretching of the OH group, and 3300 cm^{-1}, indicating stretching of the NH group. At a wavelength of 1570 cm^{-1} is the stretching of the weak NH group (II amide). At a wavelength of 1654 cm^{-1} is the stretching of the C=O group, and at 2928 cm^{-1} is the stretching of the C-H group. In sample C, which uses chitosan, the wavelengths are nearly the same for each OH/NH group at 3447, the NH amide at 1597, the C=O at 1659, and the C-H at 2926.

For other functional groups, the results are compared with research by Saputro and Ovita [30], who produced a bioplastic film from chitosan and ganyong starch. From the results of this study shows the wavelength of each functional group: -OH/NH$_2$ 3441.01 cm^{-1}, -CH 2877.79 cm^{-1}, C=O / C-N amide 1658.79 cm^{-1}, NH amine 1597.06 cm^{-1}, CH amine 1381.03 cm^{-1}, C-O 1033.85 cm^{-1}, and C-C 894.97 cm^{-1}, also shows similar results to sample F for the wavelength of each functional group -OH/NH$_2$ 3447 cm^{-1}, -CH 2926 cm^{-1}, C=O / C-N amide 1659 cm^{-1}, NH amine 1597 cm^{-1}, CH amine 1375 cm^{-1}, C-O 1007 cm^{-1}, and C-C 895 cm^{-1}. The presence of a strong and broad absorption band with a wavelength area in the range of 3400 cm^{-1} indicates the presence of -OH groups that overlap with -NH$_2$. The broadening of the spectrum area at a wavelength of 3400-3463 cm^{-1} is caused by the increase in -OH groups due to the addition of starch to each sample. The absorption band at 3429.43 cm^{-1} corresponds to an O–H (carboxyl) bond, signifying the presence of hydrogen bonding. This O–H vibration also suggests the contribution of sorbitol within the bioplastic structure [8].

Recent studies have highlighted the growing potential of starch-based bioplastics as sustainable alternatives to conventional plastics due to their biodegradability, renewability, and environmental compatibility. However, native starch materials often exhibit limitations in thermal and mechanical properties, which has led to the development of reinforced systems using inorganic fillers. The incorporation of zinc oxide (ZnO) nanoparticles has been widely reported to improve thermal stability, mechanical strength, and barrier properties of starch-based bioplastics due to their ability to interact with the polymer matrix and act as heat-resistant components [31], [32], [33].

Recent studies highlight the potential of agricultural waste, such as durian peel, as a starch source for biodegradable bioplastics due to its availability and lignocellulosic content. Durian peel-based composites have been reported to improve thermal stability and structural properties [12]. In addition, incorporating ZnO as an inorganic filler enhances the thermal and mechanical performance of starch-based bioplastics by serving as a heat-resistant reinforcing phase. ZnO nanofillers have been shown to increase crystallinity and thermal stability, as indicated by higher residual mass and improved degradation behavior [34], [35]. Thermogravimetric analysis (TGA) is widely used to evaluate the degradation behavior of starch-based composites, typically exhibiting stages associated with moisture loss, polymer decomposition, and char formation. These stages are important for understanding thermal stability and the influence of composition and fillers [30]. Recent studies also emphasize the correlation between FTIR and TGA results to better understand structure–property relationships and optimize bioplastic performance [36].

Compared with conventional plastics such as low-density polyethylene (LDPE), starch-based bioplastics exhibit lower thermal stability due to their hydrophilic and biodegradable nature. Nevertheless, incorporating ZnO and chitosan fillers improved thermal stability, reducing the performance gap while maintaining biodegradability. These findings highlight the potential of durian peel starch-based bioplastics as sustainable alternatives to petroleum-based plastics. However, this study was limited to thermal and chemical characterization. Key properties, including tensile strength, elongation at break, water resistance, water vapor permeability, barrier performance, biodegradability, and long-term durability, should be investigated in future studies to validate their suitability for practical packaging applications.

4. Conclusion

This study demonstrated that the tapioca starch–durian peel starch ratio and filler type significantly influence the thermal behavior of starch-based bioplastics. TGA-DTA analysis showed multi-stage thermal degradation for all formulations, with the 1:0.5 starch–durian peel ratio exhibiting the highest thermal stability. Chitosan and ZnO-filled bioplastics showed the lowest mass losses (77.024% and 76.294%, respectively), while higher lignocellulosic content increased residual char and improved heat resistance. FTIR analysis confirmed that the bioplastic matrix was formed primarily through physical interactions among starch, durian peel components, sorbitol, chitosan, and ZnO, with hydrogen bonding enhancing thermal stability. These findings highlight the potential of durian peel waste as a sustainable bioplastic feedstock and demonstrate the beneficial effects of chitosan and ZnO fillers. Future studies should investigate mechanical properties, water resistance, barrier performance, biodegradability, long-term durability, and optimize filler loading to support practical, environmentally friendly packaging applications.

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