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Study of Radiation Technology to Improve Properties of Sago (Metroxylon Sagu) Based Degradable Plastic

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ABSTRACT

This degradable plastic derived from modified sago starch is designed to reduce the use of synthetic polymers. In this study, we used radiation technology to improve how easily degradable materials can degrade. The gamma-ray doses used were 5 kiloGray (kGy), 10 kGy, and 20 kGy. Energy absorption analysis revealed that exposure to radiation caused a rise in the melting point of degradable plastic. The highest recorded melting point was 527.17°C at a dose of 20 kGy, with a fusion enthalpy of 562.67 J/g. Meanwhile, for plastic without radiation, the melting point was 515.54°C, and the latent heat of melting (ΔH fusion) was 694.44 J/g. In this instance, polymer degradation and exothermic peaks have been observed at without and all radiation doses.

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Thermal stability found that using zero radiation dose resulted in only a little depolymerisation and weight loss (442.06°C-511.37°C; 92.57%). However, using 10 kGy of radiation led to a higher level of depolymerisation compared to other doses, which resulted in weight loss (457.13°C to 516.70°C; 98.04%). In the chemical compound on degradable plastics without radiation dose and all radiation doses, there are C-H; OH; -CH_2-CH_2 and C=O groups, the plastic material underwent decomposition within the soil. It was characterised as both organic and hydrophilic. The biodegradation rate of irradiated plastics is twice as fast which cuts the degradation time in half when compared to no radiation exposure. Extrapolation analysis shows that all plastics will be fully degraded by nature within 7 years of burial.

Keywords: Degradable plastic, gamma-ray, process innovation, radiation, sago starch, technology

INTRODUCTION

The global oceanic ecosystem is contaminated by plastic, with an estimated accumulation of over one and a half million tons of plastic, equivalent to more than five trillion pieces. The pervasive presence of microplastic particles in the environment has recently garnered heightened scrutiny due to its detrimental impact on marine ecosystems and human health (Goh et al., 2025). Plastic has been identified as the most prevalent type of pollution found on the seafloor (Harrison et al., 2018). One solution is to use degradable plastic made from starch. The composition of sago consists of starch 80.69%, crude fiber 0.37%, water 7.21%, ash 0.11%, fat 0.56%, protein % 0.36 and carbohydrate 91.76% (Budiyanto et al., 2019). Thermoplastic starch (TPS) is a type of material made from gelatinised starch. Plastic materials derived from starch usually contain a small amount of water, which makes them brittle. Modifiers are used to prevent this brittleness. Right now, isocyanate groups are the most active in terms of reacting with the hydroxy groups of starch to make it more brittle. Polyurethane pre-polymer (PUP) with isocyanates is often used to make starch stronger. A variety of additives can be utilised in the manufacturing of plastics. These include plasticizers, which are employed to reduce brittleness and enhance flexural strength and elasticity. Antimicrobial agents are also used to extend the shelf life of the product. Flavour and colour additives are employed to improve the sensory characteristics and general appeal of the product (Beikzadeh et al., 2020).

The novelty of this research is to use gamma radiation rays in kilogray doses on modified sago starch-based degradable plastics. Polymer radiation processing is an environmentally friendly technology. It has low pollution and low energy consumption. It is also used for polymer recycling and other environmental protection activities. The quantity of radiation in the form of electron beams and the measured dose of gamma radiation in the produced materials are expressed in kilo gray (kGy) (Sujayasree & Fasludeen, 2017). The physicochemical properties of sago starch were found to be subject to alteration due to gamma irradiation, with the extent of change contingent upon the applied dose level. The study found that the apparent amylose content and swelling power of irradiated sago starch were decreased significantly, while reducing sugars and starch solubility increased due to degradation (Othman et al., 2015). Arafat et al. (2014) examined pure sago starch films and films that were mixed with 2-Hydroxyethylmethacrylate. They exposed the films to gamma irradiation to create photo-crosslinking. Exposure to gamma radiation made the films stronger, more elastic, and more flexible. Gamma-irradiated films also had a higher glass transition temperature than untreated films, as shown by thermomechanical analysis. In a study by Muradov et al. (2023), graphene oxide/polyvinyl alcohol nanocomposites were exposed to different levels of gamma (γ) radiation (1, 50, and 150 mRad). Changes in structure, optical properties, and morphology were observed after exposure to different doses of radiation. In this study, the decomposition and oxidation of residual graphite under the influence of γ radiation were observed. The band gap value of the sample demonstrated a decrease in response to increasing gamma radiation.

Thermoplastic starch (TPS) is a type of material that is made from gelatinised starch. The purpose of gelatinisation is to disrupt the crystalline molecular structure of starch particles. The process is comprised of three stages: initial swelling, melting of natural crystalline structures, and solubilisation of the macromolecules. The materials in question have the capacity to undergo reheating or melting, thereby enabling the formation of new shapes without significant alterations to their physical properties. This phenomenon can be attributed to the absence of chemical cross-links within the polymers (Jiang et al., 2020). Plastic materials derived from starch typically contain a minimal amount of water, which makes them brittle. Modifiers are used to prevent this fragility. Right now, the isocyanate group is the most active when it comes to reacting with the hydroxy group of starch to improve brittleness. Polyurethane pre-polymer (PUP) with isocyanate is often used to make starches stronger.

A variety of additives can be utilised in the manufacturing of plastics. These include plasticizers, which are employed to reduce brittleness and enhance flexural strength and elasticity. Antimicrobial agents are also used to extend the shelf life of the product. Flavour and colour additives are employed to improve the sensory characteristics and general appeal of the product (Beikzadeh et al., 2020). Liu et al. (2008) conducted a study on a film comprising a blend of castor oil-based polyurethane (PU) and poly-p-phenylene-diamine soya protein (PDSP). FTIR, DSC, DMA, and SEM tested the mixed films' morphology, thermal, and mechanical properties. Both components work well with many ratios due to hydrogen bonding or chemically cross-linked bonds between PU and PDSP. The addition of PU makes PU/PDSP films more elongated, thermally stable, and water resistant. Lu et al. (2005) prepared PU derived from canola oil-based polyols using it to control the water susceptibility of glycerol-plasticised starch. Results demonstrated that plasticised glycerol starch can be formulated with other raw materials to improve its strength. The film is also made more water repellent by adding PU to the starch mixture. The PUP is produced from diphenylmethane diisocyanate and polyols from castor oil. This change creates a filler material that makes small particles. These particles are sago starch thermoplastics. PUP is used to stick the starch to the other materials through a process called urethane bonding (Wu et al., 2008).

However, the addition of PUP into thermoplastic starch needs to be done carefully, considering that PUP will affect plastic biodegradability. Researchers explored how the size of the plastic particles affects how easily polybutylene sebacate plastic pellets can be broken down. Four different particle sizes were used in the study. First, the particles were measured directly, and then the images were studied. Samples were placed in a machine that grinds them up. This process was done for different samples for 138 days. The first part of the biodegradation process calculates the rate of biodegradability using something called straight-line interpolation. This calculation is based on the total land area available (Chinaglia et al., 2018). The recycled polypropylene was compounded with degradable polymers, including polylactic acid (PLA), polyhydroxybutyrate (PHB), and additionally thermoplastic starch. Thermal and mechanical changes were evaluated. The findings indicated that the incorporation of bio-based polymers into PP recycled materials did not result in alterations to the melting point or the melt flow index. It has been determined that an increase in the quantity of bio-based polymers beyond 5 wt.% results in alterations to the mechanical properties (Samper et al., 2018).

In their study, Hammache et al. (2020) examined the impact of blending thermoplastic polyesters (TPS) and polypropylenes (PP/PE), both with and without the incorporation of a compatibilizer. The addition of nano-clay to these nanocomposites serves to enhance their thermomechanical characteristics. The byproducts that are produced when the thermoplastic starch breaks down help to protect the PP/PE and PP/PE-g-MA/PE from harm caused by heat. Obasi et al. (2015) investigated the tensile, water absorption, and biodegradability of potato starch-filled polypropylene blends. Polypropylene grafted maleic anhydride (PP-g-MA) was used to help the different materials work well together. The tensile strength and elasticity of the material are directly influenced by the starch content. However, Young's modulus exhibits a direct correlation with the starch content. The incorporation of PP-g-MA into the blends resulted in enhancements to the tensile strength and elongation at break. However, these values remained lower than those observed for the pure polymer (Hammache et al., 2020). Dewi et al. (2019) found that the biodegradability of thermoplastic starch with polypropylene matrix was below 2 years by soil burier; however, it depends on soil condition and rain intensity. In order to enhance the process of decomposition through the use of novel technologies is essential. For instance, the application of radiation technology has shown to be a successful method in this capacity.

The modification of polymers through the utilisation of high-energy radiations, such as gamma rays and the electron beam, constitutes a highly established domain within the spectrum of research and development (Singh et al., 2022). Plastic waste can be turned into useful things using radiation technology. This helps the environment and creates new materials. Plastic materials are characterised by their strength, durability, resistance to water, low density, ease of molding, and capacity for recycling (Cheon et al., 2021). A variety of research has previously examined the potential of end-of-life polymer properties to be enhanced by means of irradiation. The types of irradiation that have been examined include electron beam irradiation, beta irradiation, and gamma ray irradiation (González Niño et al., 2023). The utilisation of gamma and e-beam radiation has emerged as the predominant approach in cross-linking, cross-linking-compatibilisation, and cross-linking grafting of diverse polymer mixtures and composite systems (Naikwadi et al., 2022). This procedure is affordable, can be used in many ways, is easy to repeat, and does not create waste. The best way to prepare high-purity products, achieve successful modifications, and guarantee results is to use a radiation alternative to modify polymers and their hybrids.

Cieśla and Abramowska (2021) present a discussion of the influence of irradiation on the functional characteristics of starches with biodegradable properties. The following investigation focusses on the properties and characteristics of PVA films. The analysis is about whether the material can be used to package products (especially food) that are expected to be decontaminated by radiation. It also looks at whether the material can be changed by exposure to radiation. The results show that using doses of around 25 kGy doesn't cause major changes in the properties of starch films. In their study, Cheon et al. (2021) examined the effects of incorporating plastic waste into cement composites, specifically focussing on the impact of gamma irradiation in modifying the properties of these composite materials. An evaluation of the material's mechanical properties was conducted. The utilisation of modified plastic aggregates in lieu of conventional plastic aggregates has been demonstrated to enhance the physicochemical performance of cement based composites by up to 70%. Researchers Lee et al. (2021) studied how modifying plastic materials with gamma irradiation could be used in cement-based composites. They compared this method with using non-irradiated plastics as an additive. The result showed irradiation has increased plastic compressive strength. Researchers are just starting to explore using X-rays to sterilize things. The degradation of materials like polyethylene, polypropylene, polyester, and polystyrene was studied for every type of irradiation used, including gamma, X-ray, and UV. Other materials that were studied include rubber, EPDM, PVC, PTFE, PVDF, and cellulose (Girard-Perier et al., 2021).

Ionising radiation breaks down the organic materials into pieces. People are interested in how radiation changes the chemicals in natural and man-made polymers. This knowledge can help improve industrial processes. Polysaccharides and their derivatives exposed to ionising radiation have long been recognised as a type of degradable polymer. The first event observed during polysaccharide radiation leads to the breakdown of intermolecular and intramolecular hydrogen bonding, and the degree of crystallinity of the material is reduced. Polymer materials can be improved by exposure to radiation in ways that make them stronger. In this study, our team will discuss how the addition of irradiation affects the thermal and chemical properties of sago starch-based degradable plastic. We will also explore how this change affects its biodegradability, with the goal of enhancing its performance.

MATERIALS AND METHODS

The materials utilised in this investigation encompassed local agricultural sago starch, various synthetic polymers such as PP/PE, glycerin, and chitosans, as well as isocyanate-based compounds (MDI), synthetic polyol, and $CaCO_3$-based compatibility agents. The materials were utilised in their original state, without undergoing additional processing. The research method was comprised of several steps. First, thermoplastic starch was produced. Next, thermoplastic starch was blended with PP/PE. Finally, the plastic was irradiated with gamma rays.

Preparation of Thermoplastic Starch

The sago flour and water utilised in this experiment were measured precisely according to the established formulation, and subsequently combined to form the mixture. The mixture was subjected to a thermal treatment and agitated at a temperature of 70°C for a duration of 25 minutes, resulting in its conversion into a gelatinous state. Thermoplastic starch (TPS) was modified by in situ mechanism by adding MDI and polyol in a predetermined ratio. Glycerin was introduced into the mixture at a concentration of 10%, along with chitosan and $CaCO_3$. The mixture was then agitated until achieving a homogeneous consistency. The homogeneous mixture was dried for 24 hours at 80°C. Once it dries, the mix will form into cracks, which will then be crushed into finer pieces.

Production of Thermoplastic Starch

Thermoplastic starch in the form of a crust was ground to a fine size to make it easier to mix. PP/PE melts at 110°C, they were melted and mixed with thermoplastic starch. A crusher broke the mixture down into small pieces, and an extruder turned these pieces into plastic pellets. Injection molding machines were used to mold the plastic pellets into household products such as plates, bowls and vases.

Irradiation Process

When the plastic product was ready, a radiation technique with various doses (in Kilo Gray) was used to determine the optimal dose for the irradiation process. The various radiation doses of gammas rays were 5 kGy, 10 kGy, and 20 kGy, using a Multipurpose Panorama Irradiator (IPRASENA). The radiation source comes from a ^{60}Co isotope source. 20 kGy is a radiation dose high enough to form many radical sites (Sujayasree & Fasludeen, 2017). The irradiation was performed at the National Nuclear Energy Agency's Isotope and Radiation Technology Research and Development Center (P3TIR, Jakarta).

Thermal, Chemical, and Biodegradability Analysis

Thermal characteristics were determined using differential scanning calorimetric (DSC) and thermal gravimetry analysis (TGA) to determine thermal stability. The functional groups contained in plastic were analysed using Fourier Transformation Infrared (FTIR) and biodegradability through soil planting (buried) method using ASTM D5338 for a year starting from September 2021 to September 2022.

RESULTS AND DISCUSSION

Radiation processing of polymers is the treatment of polymer materials with ionising radiation for the purpose of modification of their physical and chemical properties and enhancement of their properties. Radiation processing of polymers is a part of non-power applications. It consists mainly of crosslinking, curing, grafting, and degradation. Commercial-scale ion beam processing of polymer materials has been shown to be a very effective means of polymer physical property improvement. Differential Scanning Calorimetry (DSC) and Thermal Gravimetric Analysis (TGA) are used for thermal testing. Thermal analysis of degradable plastics was performed using different radiation doses to determine thermal stability. In addition, the influence of radiation on the chemical groups and the correlation with thermal stability have been investigated.

Differential Scanning Calorimetric (DSC) Analysis

High energy ionising radiation could be provided by radioisotope sources and electronic accelerators. Some polymers would be cross-linked, while others would be degraded after exposure to radiation. Cross-linking would improve the polymer's mechanical, thermal, and other properties. Three radiation doses of 5 kGy, 10 kGy, and 20 kGy were used for the DSC analysis. DSC is an instrument that quantifies the temperature of material change. The resulting data is a curve of heat flow to the sample minus the heat flow to the references against time or temperature.

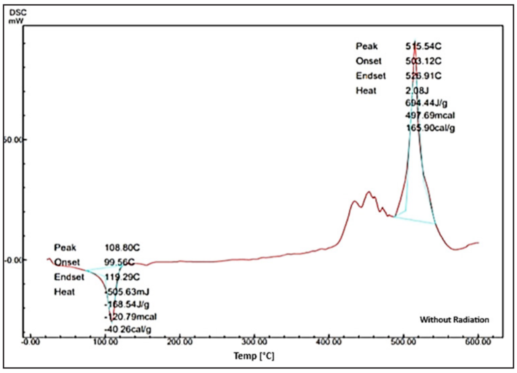

Figure 1. DSC analysis of plastic without radiation

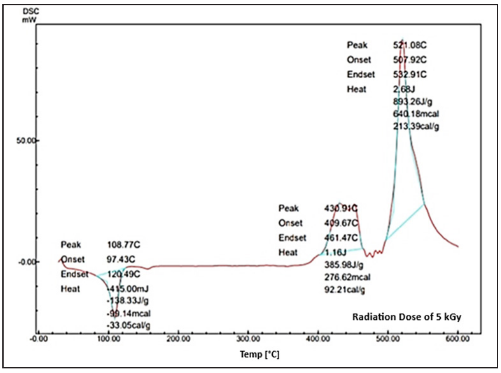

Figure 2. DSC analysis with 5 kGy

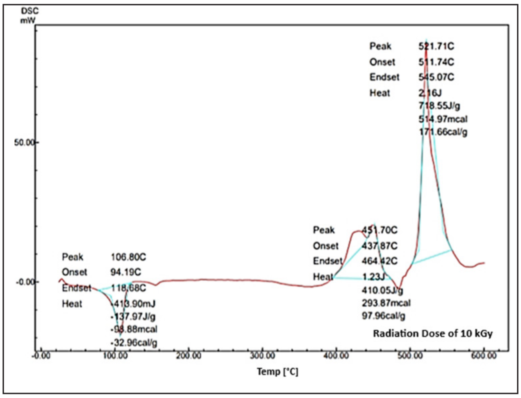

Figure 3. DSC analysis with 10 kGy

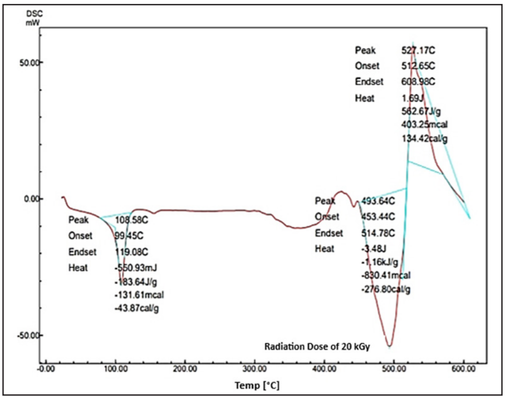

Figure 4. DSC analysis with 20 kGy

Table 1

DSC analysis dataset summary on degradable plastics without radiation

Area (0 kGy)	**Normalized (J/g)**	**Onset (°C)**	**Endset (°C)**	**Peak (°C)**
I	-168.54	99.56	119.29	108.80
II	694.44	503.12	525.91	515.54
III	893.26	507.92	532.91	521.08

Table 2

DSC analysis dataset summary on degradable plastics with 5 kGy dose

Area (5 kGy)	**Normalized (J/g)**	**Onset (°C)**	**Endset (°C)**	**Peak (°C)**
I	-138.33	97.43	120.49	108.77
II	385.96	409.67	461.47	430.91
III	893.26	507.92	532.91	521.08

Table 3

DSC analysis dataset summary on degradable plastics with 10 kGy dose

Area (10 kGy)	Normalized (J/g)	Onset (°C)	Endset (°C)	Peak (°C)
I	-137.97	106.80	118.68	106.80
II	410.05	451.70	464.42	451.70
III	718.55	521.71	545.07	521.71

Table 4

DSC analysis dataset summary on degradable plastics with 20 kGy dose

Area (20 kGy)	Normalized (kJ/g) (J/g)	Onset (°C)	Endset (°C)	Peak (°C)
I	-183.64	99.45	119.08	108.58
II	-1.16	453.44	453.44	493.64
III	-562.67	512.65	608.98	527.17

There were two heats at no radiation dose, which were observed during the second heat. While at radiation doses of 5 kGy, 10 kGy and 20 kGy there were three heats in the DSC analysis of this study, but this study observed it during the third heating. The peak of the curve for sago starch-based degradable plastics looks very sharp in the third area. DSC test results for plastic without radiation, Table 1 and Figure 1 showed the melting point was 515.54°C, and the latent heat of melting (△H of fusion) was 694.44 J/g. Meanwhile, for plastic with 5 kGy, as shown in Table 2 and Figure 2, the melting point was 521.08°C and △H of fusion was 893.26 J/g. Plastic with a radiation dose of 10 kGy showed a melting point of 521.71°C and △H of fusion was 718.55 J/g and plastic with a radiation dose of 20 kGy showed a melting point of 527.17°C and △H of fusion was 562.67 J/g, as shown in Figures 3 and 4, or clearly can be seen in Tables 3 and 4 respectively. At all doses, the peaks in the third phase were attributed to thermal events due to polymer degradation, with exothermic peaks (Al-Masry et al., 2021). The melting point of the degradable plastic without radiation was higher than the melting point of sago thermoplastic only due to the cross-link formation that occurred between starch and polyurethane prepolymer (PUP) and PP/PE during plastic synthesis. The melting point of sago thermoplastic was only 70°C, known as the gelatinisation point. The addition of PUP to the starch matrix resulted in an elevated melting point of the thermoplastic. A higher melting point indicates that more cross-linking has been performed. The presence of hydrogen bonds within the plastic material is a critical factor that contributes to its melting point. It has been demonstrated that the melting point of a given plastic increases in proportion to the number of hydrogen bonds present in the material. This is due to the greater energy required to break the bond (Gunawardene et al., 2021). From Figure 1 to Figure 4, it can be seen that there was an increase in the melting value of degradable plastic after applying gamma radiation, with a higher melting point observed at exposure of 20 kGy radiation dose.

A significant increase was also applied to the heat of fusion of degradable plastic after exposure to radiation, as seen in Figure 2. The difference studied in DSC analysis for doses without radiation, 5 kGy, 10 kGy and 20 kGy is that the radiation dose of 5 kGy has a very significant latent heat value compared to no radiation and other doses. Comparing the heat of fusion between sample without radiation and after 5 kGy radiation dose increases the latent heat of fusion (694.44 J/g before radiation and 893.26 J/g after 5 kGy radiation dose). However, when exposed to higher gamma radiation doses, latent heat did not rise with a clear pattern and seemed not to be influenced by the radiation dose applied; meanwhile, radiation has provided significant differences in the heat of fusion of plastic before and after radiation. Further analysis has given a decreasing trend when the radiation dose was higher. It can be seen from the result provided by 10 kGy and 20 kGy doses that the latent heat of fusion was 718.55 J/g and 562.67 J/g, respectively. Analysing the melting point and heat of fusion obtained, it can be concluded that the best radiation dose was 5 kGy with the highest latent heat of fusion and good melting point. Girard-Perier et al. (2021) studied how X-rays, electron beams, and gamma rays affect the properties of multilayer films made of PE/EVOH/PE. They found that the films' heat-related characteristics are not greatly changed by the type of irradiation, as seen in a process that measures heat changes using a calorimeter. This material is also expected to have similar physical and mechanical properties. However, Svoboda et al. (2021) mentioned that the results of the measurements of how fast the materials HDPE and PP crystallised were greatly influenced by the process of irradiation. These measurements were taken using two different methods: DSC and high-temperature scanning optical microscopy.

Thermogravimetric Analysis (TGA)

TGA is a technique that has been developed for the purpose of measuring changes in weight as a function of heating temperature. The weight loss (vapour emission) or sample weight increase (gas fixation) of the material is determined by this characterisation. This technique is commonly used in the determination of sample purity, decomposition, thermal decomposition, and chemical response where material weight is altered by adsorption, desorption, and chemical kinetics. The resulting data is a curve of weight against time and temperature.

From Figure 5, it can be seen that the sample started to decompose at 40°C and finally stopped decomposition at 600°C. The variation in mass of a given substance was determined as a function of either heat or duration by subjecting the specimen to a regulated temperature programme within a controlled atmosphere. The percentage of decomposition was 99.9%. After being exposed to a radiation dose of 5 kGy, 10 kGy,

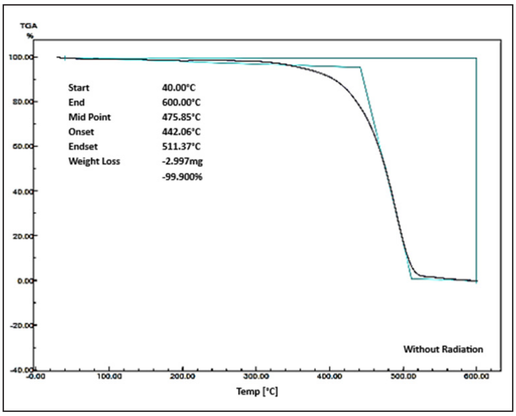

Figure 5. TGA analysis of plastic without radiation

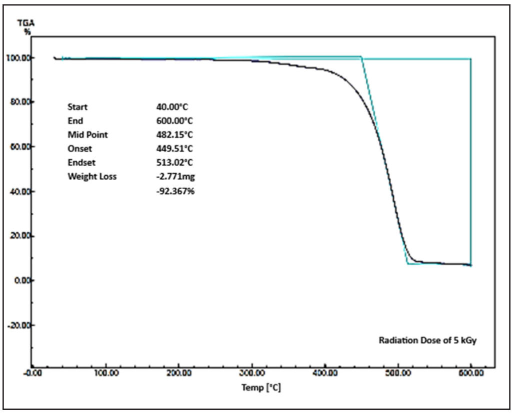

Figure 6. TGA analysis with 5 kGy

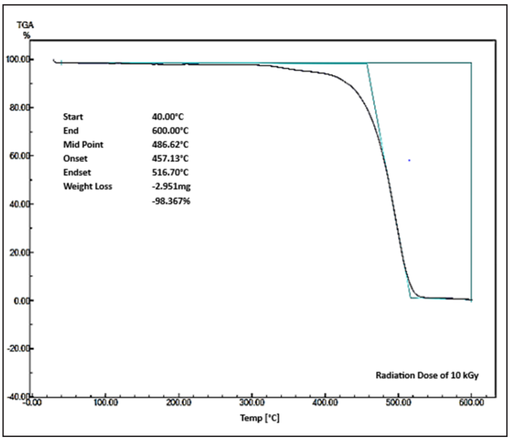

Figure 7. TGA analysis with 10 kGy

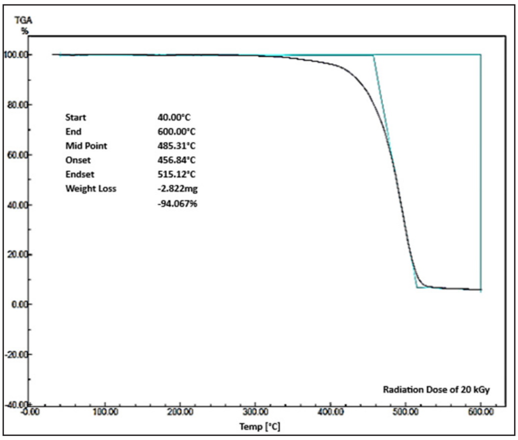

Figure 8. TGA analysis with 20 kGy

and 20 kGy, all samples showed a similar decomposition graph pattern starting at 40°C and stopping at 600°C, as shown in Figures 6, 7, and 8. The onset of extreme weight loss, characterised by the formation of crystalline structures, has been observed within a specific temperature range, depending on the radiation dosage. Specifically, the onset occurs within the temperature range of (442.06°C -511.37°C) without radiation dose, (449.51°C-513.02°C) with 5 kGy, (457.13°C-516.70°C) with 10 kGy, and (456.84°C -515.12°C) with 20 kGy. The decomposition rates were different, although not significant, which were 92.57%, 98.36%, and 94.06% for 5 kGy, 10 kGy, and 20 kGy, respectively. The findings indicate the presence of 2.99 mg, 2.77 mg, 2.951 mg, and 2.822 mg of plastic material, respectively. The utilisation of a zero-radiation dose has been shown to elicit minimal depolymerisation, while the application of a 10 kGy radiation dose has been observed to yield a higher level of depolymerisation compared to other doses. In relation to the application of radiation dose, no statistically significant alterations were detected at periods exhibiting elevated mass loss. A correlation has been demonstrated between the mass of residue left after decomposition and the thermal resistance of the material at each of the different radiation doses (Da Costa et al., 2023). This finding suggests a correlation between the quantity of residue remaining after the process of decomposition and the thermal resistance of the material utilised. It is posited that materials with greater weight of residue tend to demonstrate higher thermal resistance (Santos et al., 2025). This study shows that degradable plastics exhibit a substantial degree of thermal degradation. The samples showed signs of hydrogen group loss, decomposition, depolymerisation, and cracking of carbon chains in the starch structure (Sanyang et al., 2015). The thermal temperature of degradable plastic has undergone endothermic processes, although a small decrease in decomposition rate occurred after the sample was exposed to gamma radiation compared to before. No clear pattern can be observed related to the increasing radiation dose toward the decomposition rate. The highest decomposition rate was obtained at 10 kGy radiation dose. However, the decomposition rate of all doses was above 90%, and this has shown that gamma radiation does not affect the thermal stability of degradable plastic; hence, the thermal characteristic can still be maintained. This analysis is needed for application to ensure degradable plastic can retain heat. One possibility for the different decomposition rates was the presence of impurities during plastic synthesis.

Cinan et al. (2021) studied how well gamma irradiation worked and lead oxide (PbO) protected other materials. They used different amounts of PbO in two types of materials: a block copolymer made of cross-linked polystyrene and polyethylene glycol (PS-b-PEG), and a nanocomposite made of polystyrene-b-polyethyleneeglycol-boron nitride (PS-b-PEG-BN). The TGA thermogram results showed that the structure of the polymer-based composites studied was unaffected by the implemented radiation when the materials PbO-doped cross-linked PS-b-PEG block copolymer and PbO-doped PS-b-PEG-BN nanocomposite were used. Elsawy et al. (2023) studied how the physical and chemical properties of degradable poly(lactic acid) (PLA) and PLA/chitosan nano composites change when they are exposed to gamma irradiation. They found that the Tg and Tm for PLA_3CsNP irradiated in solution shifted slightly lower when the dose of gamma irradiation increased (5-40 kGy). The crystallinity of the material has decreased slightly. The process of crystal formation happens at a higher temperature and over a wider range of temperatures as the amount of irradiation increases. A comparative study induced by oxidising gamma-ray irradiation on polyethylene, poly(vinylidene fluoride), and polytetrafluoroethylene was conducted by Shim et al. (2022). It has been demonstrated that polytetrafluoroethylene (PTFE) exhibits diminished oxidation and enhanced heat-resistant properties following an absorption dose of 500 kGy.

Fourier-Transform Infrared Spectroscopy (FTIR) Analysis

FTIR is an instrument that works on the principles of spectroscopy. Infrared spectroscopy, because of its very complex spectrum consisting of many peaks, is useful for identifying organic compounds. The functional group is a specific substituent or part in a molecule responsible for these molecules' chemical reaction characteristics. The chemical composition of the same functional group is the same or similar, regardless of the size of the molecule. The main functional group area is 4000-1500 cm^{-1}; meanwhile, the fingerprint area is about 1000-1500 cm^{-1} and usually has a very diverse and varied absorption and specificity.

From Figure 9, it can be seen that C=O of the ester group of the polyurethane prepolymer (PUP) occurred at 1647.21 cm^{-1}. The absorption area range for the ester group is 1650-1900 cm^{-1}; meanwhile, C-H bending appeared at 1458.18 cm^{-1}. OH groups of polyols were shown at wavelengths of 3390.86 cm^{-1}. The wave number 2868.15 cm^{-1} was the C-H stretching of the CH_3 polypropylene group, and wave number 1082.07 cm^{-1} was the -CH_2-CH_2- group has an absorption band in its fingerprint region, which is typical for polypropylene. A wave that shows a typical bending of the C-O functional group (C-O bond) was varied from 1000-1300 cm^{-1}, depending on the compound type. The bond between grafted polypropylene plastic with starch, supported by a wave number of 1647.21 cm^{-1}, indicates the C=C functional group of starch and cross-linked polypropylene.

Figure 10 shows FTIR analysis for the sample radiated with 5 kGy gamma dose. The C=O of the ester group of the polyurethane prepolymer occurred at 1647.21 cm^{-1}, exactly the same as the sample without radiation. OH groups of polyols appeared at wavelengths of 3361.93 cm^{-1}, a little bit different from the sample without radiation; the same thing also applies to C-H bending, which appeared at 1467.83 cm^{-1}. Another difference can be observed for wave number 2943.37 cm^{-1} was the C-H stretching of the CH_3 polypropylene group, and wave number 1155.36 cm^{-1} was the absorption band of the -CH_2-CH_2- Group in the fingerprint region, which is typical for polypropylene. Figure 11 shows FTIR analysis for a sample radiated with 10 kGy gamma doses. The C=O of the ester group of the polyurethane prepolymer occurred at 1805.37 cm^{-1}, different with a sample without radiation and a sample radiated with a 5 kGy dose. OH groups of polyols appeared at wavelengths of 3390.86 cm^{-1}, exactly the same as the sample without radiation. The wavenumber was 2941.44 cm^{-1}, which is the C-H stretch of the CH_3 polypropylene group. The 1159.22 cm^{-1} wave was a specific frequency of light that was absorbed by the -CH_2-CH_2- chemical structure in the sample, which is typical for polypropylene is almost the same with sample radiated with 5 kGy dose.

Figure 12 shows FTIR analysis for a sample radiated with 20 kGy gamma dose. The C=O of the ester group of the polyurethane occurred at 1807.30 cm^{-1} characterises the formation of ester groups, almost the same as the sample radiated with a 10 kGy dose. OH groups of polyols appeared at wavelengths of 2918,30 cm^{-1}, almost the same as the sample

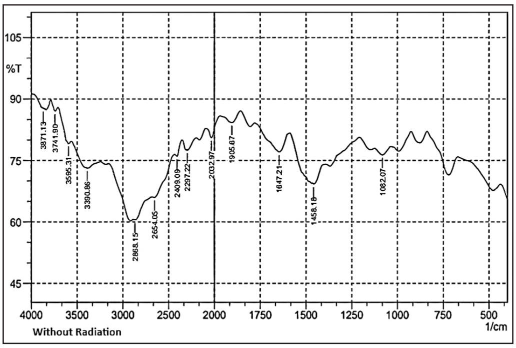

Figure 9. FTIR analysis of plastic without radiation

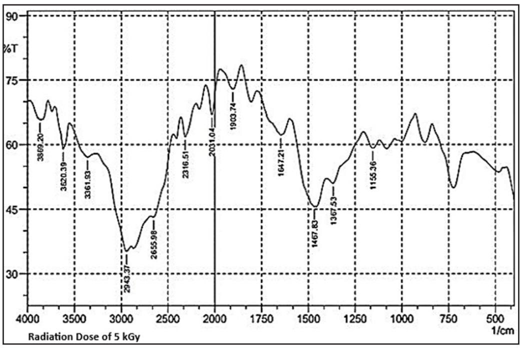

Figure 10. FTIR analysis with 5 kGy

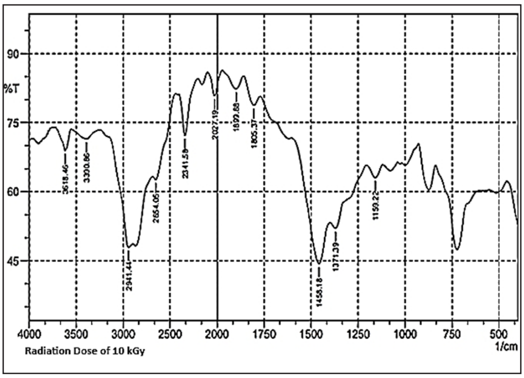

Figure 11. FTIR analysis with 10 kGy

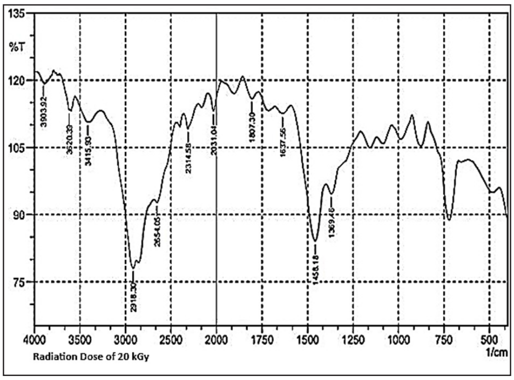

Figure 12. FTIR analysis with 20 kGy

radiated with 5 kGy and 10 kGy doses. The wave number of 2654.06 cm^{-1} was the C-H stretching of the CH_3 polypropylene group is the same as the sample radiated with 5 kGy and 10 kGy doses, and the wave number of 1150.00 cm^{-1} was the absorption band of the -CH_2-CH_2- group in the fingerprint region which is typical for polypropylene. This value was almost the same as the sample radiated with 5 kGy and 10 kGy doses. Vasile et al. (2022) studied whether exposing certain materials to high-levels of gamma radiation would affect the materials. The materials in question were PLA-based blends and biocomposites containing rosemary ethanolic extract and chitosan. The bands related to the absorption of water and carbonyl groups changed a little after being exposed to the radiation. The samples had a strong absorption band around 3506 cm^{-1} in the 3400–3600 cm^{-1} range of the FTIR spectrum, particularly in the case of PLA, which corresponds to OH groups in alcohols, hydroperoxides, and carboxylic acids. The intensity of this band increases with the dose of radiation used (10, 20, 30 kGy) after exposure to gamma radiation.

As varied quantities of radiation doses were incorporated into the material, the stretching and flexing carbonyl (C=O) bands were distinctly discernible in all spectra, with their intensity exhibiting a direct correlation with the increase in radiation dosage. In addition, when radiation doses of 10 kGy and 20 kGy were introduced to the degradable plastics, distinct characteristic band shapes of 1680-1750 cm^{-1} were detected. Peaks emerged at 1805.37 cm^{-1} and 1807.30 cm^{-1}. The intensity of the characteristic bands associated with degradable plastics appears to be significantly influenced by the radiation dose intensity. Subsequently, the isocyanate groups incorporated within the PUP react with the hydroxyl groups of the starch, thereby forming urethane bonds and ensuring the starch granules are thoroughly coated by the PUP coating (Küster et al., 2025). Furthermore, an increase in the proportion of PUP was observed to result in an enhancement of both the thermostability and hydrophobicity of the materials (Kong et al., 2023). The FTIR analysis revealed the presence of organic groups within the content composition of the respective groups. Therefore, degradable plastic has hydrophilic properties, meaning it is attracted to water. Consequently, when plastic is discarded in a natural environment, it is rapidly degraded by the soil.

Biodegradability Rate Analysis

Degradation can be classified into two distinct categories: chain-cutting and chain-linking, otherwise known as cross-linking, when organic matter is irradiated with ionising radiation. The recognition of the possibility of utilising radiation to enhance industry has led to a notable surge in inquiry concerning the radiation-degrading chemistry of naturally and synthetically derived polymers. Polysaccharides and their derivatives exposed to ionising radiation have long been recognised as a type of degradable polymer. The first event observed during polysaccharide irradiation caused a breakdown of the intermolecular and intramolecular hydrogen bonding systems. As a result, chain stiffness is affected by intramolecular hydrogen bonding. The ASTM D5988 standard was used to conduct the biodegradability test. The temperature and pH used in the biodegradability analysis at 32°C and 5.5 – 7 are generally suitable for biodegradation processes, while the soil moisture for burying degradable plastics with optimal moisture depends on the environmental conditions.

Table 5 and Figure 13 show that the biodegradability rate of plastic without radiation after one year was approximately 15%. Meanwhile, the biodegradability rate of plastic after radiation was 18-29%. Plastic loss weight step by step as a time function. Weight reduction behaviour was observed to be almost similar for all samples. The changes observed were recorded every 3 months until the one-year observation period. Some physical appearance can be seen, such as plastic colour fading and the plastic surface becoming dull and pale. In the beginning, the colour looks bright and shining. Soil microbes attack the plastic surface and damage it until plastic breaks. Previous research using film samples showed

Table 5
Plastic weight loss and biodegradability rate of different radiation doses

Radiation dose (kGy)	Weight (g)					Weight lost (g)	Biodegradation rate (%)
	Sept 2021	Dec 2021	March 2022	June 2022	Sept 2022		
0	118.6	114.3	110.5	106.8	101.1	17.5	14.75
5	118.7	110.1	105.0	101.4	96.3	22.4	18.87
10	118.4	108.8	102.1	97.3	91.7	26.7	22.55
20	118.6	112.2	96.2	90.5	84.2	34.4	29.00

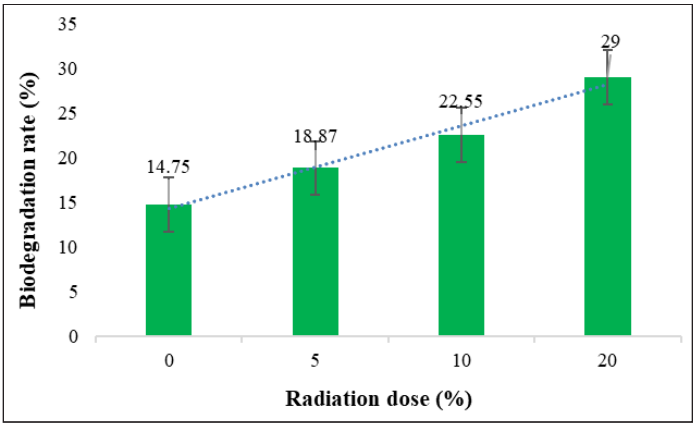

Figure 13. Plastic biodegradability rate of different radiation doses

that plastic without radiation decomposed for about 2 years, depending on soil conditions and rainfall rate (Dewi et al., 2019). However, it was not similar to this product because of the big difference in solidity, thickness, and shape of the sample used.

At that moment, the product buried was a vase product, and it was much thinner than the current plate product used for the soil burial test. The thickness was different for each product type depending on the molding. The plastic vase product was thinner compared to the plate. The biodegradability rate of the plastic vase product was above 50% in one-year soil burial, as can be seen from Figure 14. Plastic thickness significantly influences the biodegradability rate because it requires time for soil microbes to degrade it and more microbes to attack the plastic surface and digest it. Radiated plastic shows a higher biodegradability rate and increases with higher radiation doses given. Plastic with a 20 kGy dose has a 29% biodegradability rate, which means a higher radiation dose will give faster time for plastic decomposition in soil. When compared with plastic without radiation, the biodegradability rate of radiated plastic was twice as fast. Hence, it can be concluded that radiation technology can increase plastic biodegradability rate and may significantly reduce the time for plastic waste to decompose naturally.

Figure 14. Biodegradability rate of plastic vase after one-year soil burial

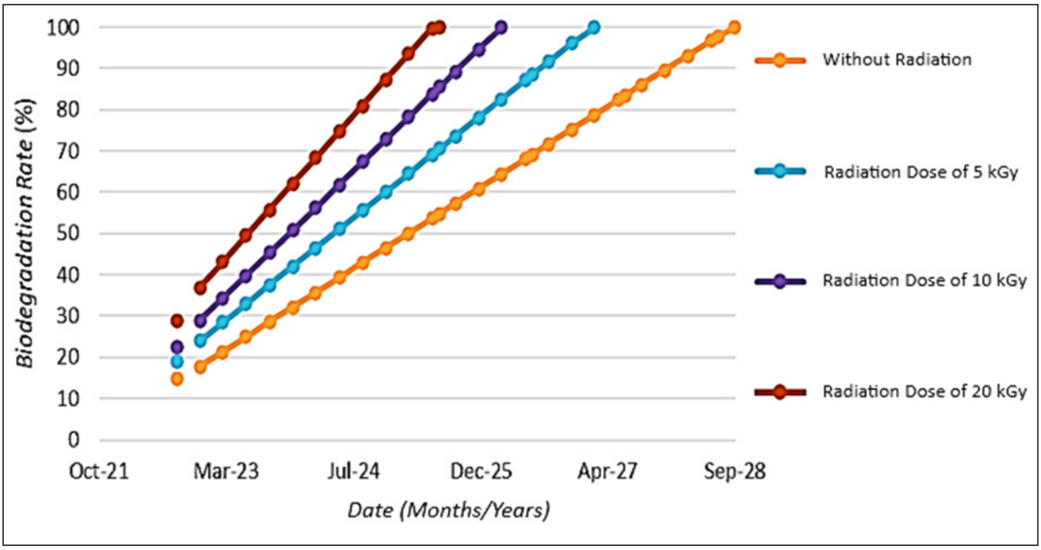

Figure 15. Biodegradability rate of the plastic vase after one-year soil burial

Figure 15 shows an extrapolation graph for all radiation doses. These data plot to predict when all the plastic will be 100% degraded by nature. Plastic without radiation will be fully degraded on September 2028 (in a 7-year period). When radiation is used, plastic exposed to 20 kGy dose is fully degraded on approximately 3.8 years burial (Sept 2021 to July 2025), while radiation dose of 10 kGy will take more time to be degraded, which is approximately 4.5 years (Sept 2021 to March 2026) and radiation dose of 5 kGy will be degraded approximately 5.5 years (Sept 2021-March 2027). It can be concluded that plastic produce can be fully degraded by nature. Radiation exposed to plastic can improve the degradation rate for all doses, hence shortening the degradation period and cutting off almost half of the degradation time for a 20 kGy radiation dose.

CONCLUSION

The impact of using without radiation and using radiation of degradable plastics was investigated using gamma rays. The use of radiation dose can affect the thermal properties and biodegradation rate of degradable plastics. The use of a radiation dose of 5 kGy, has the best energy absorption properties compared to other doses which have the highest latent heat of fusion and a good melting point. DSC analysis at a dose of 5 kGy showed the melting point was 521.08°C and △H of fusion was 893.26 J/g. In the thermal stability analysis, research indicates that the application of a radiation dose of 10 kGy results in a higher depolymerisation rate compared to other doses with temperatures ranging from 457.13°C to 516.70°C and a mass loss of 98.04%. The FTIR analysis revealed the presence of organic groups, and the degradable plastic exhibited hydrophilic properties, indicating its decomposition susceptibility by soil. Higher radiation doses will give faster plastic decomposition in soil. Compared with plastic without radiation, the biodegradability rate of radiated plastic was twice as fast. Plastic thickness significantly influences the biodegradability rate because it required time for soil microbes to degrade it and more microbe to attack the plastic surface and digest it. Extrapolation analysis shows that all plastic will be degraded fully by nature within 7 years of burial. The faster degradation time is obtained at 20 kGy dose radiation, which cuts off half the degradation time when compared with no radiation exposure. In this study, gamma radiation was utilised to change the properties of the product to make it more optimal without making the material radioactive. Radiation has the advantage of being safe, efficient, high precision and environmentally friendly, as it is able to reduce the use of harmful chemicals. The radiation exposure process does not cause radioactivity in the plastic material, thus ensuring safety for its users. The utilisation of radiation technology has the potential to address environmental concerns associated with conventional plastics. The utilisation of gamma radiation in the production of degradable plastics has good thermal properties and a high degree of biodegradability, which facilitates rapid decomposition in a short period of time.

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