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Evaluation of Plastic Waste Degradation Using Terahertz Spectroscopy for Material Recycling

Hitomi Sonohata [1,*], Gaku Manago [2,*], Shun Seike [3], Hidetoshi Kitawaki [1] and Tadao Tanabe [3,*]

[1] Graduate School of Global and Regional Studies, Toyo University, Tokyo 1128606, Japan; kitawaki@toyo.jp
[2] Graduate School of International Cultural Studies, Tohoku University, Miyagi 9808576, Japan
[3] Department of Engineering and Design, Shibaura Institute of Technology, Tokyo 1358548, Japan; thz.sit1927@gmail.com
* Correspondence: s4d201900028@toyo.jp (H.S.); gaku.manago.e4@tohoku.ac.jp (G.M.); tanabet@shibaura-it.ac.jp (T.T.); Tel.: +81-3-3945-8071 (H.S.); +81-22-795-7625 (G.M.); +81-3-5859-8828 (T.T.)

Abstract

In Japan, the majority of waste plastics are classified into three categories: approximately 22% are used for material recycling, 3% are used for chemical recycling, and 62% are used for thermal recycling. Thermal recycling is not considered true recycling in the EU, however. To achieve a decarbonized society, Japan must increase the share of material recycling. The accurate identification of plastic materials is essential in this regard, and while near-infrared (NIR) spectroscopy is commonly employed in analyses, it cannot be used to assess degradation levels. Plastics characterized by different degrees of degradation can reduce the quality of recycled products and require additional treatment. In this study, we irradiated artificially degraded polyethylene and polypropylene samples using Fourier transform infrared (FTIR) spectroscopy and terahertz (THz) waves and subsequently compared them with undegraded samples. Our results provide experimental confirmation that THz waves can be used to determine the degree of plastic degradation. When combined with NIR-based material identification, this method could enhance the precision and efficiency of plastic recycling, contributing to a more sustainable recycling system.

Keywords: degradation; waste plastic; recycling; material recycling; terahertz

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1. Introduction

Plastic production has increased rapidly since the 1950s, and with it, waste; as of 2015, some 6300 million metric tons of plastic waste had been generated, 79% of which had accumulated in landfills and the natural environment [1]. Microplastics are ubiquitous in air, water, and soil and have been detected in a variety of organs and tissues, including human lungs, placenta, and blood. The improper disposal of plastic waste results in a variety of issues, including marine pollution, ecological damage, and harmful effects on human health [2]. Despite rapid city- and country-level development, a key challenge remains in that many countries are not adequately equipped to introduce appropriate management systems and recycling methods that can cope with the changing composition of waste [3]. In Japan, the recycling of plastics can be divided into three main categories [4]. First, material recycling (=mechanical recycling) is a method whereby plastic waste is crushed, melted, and recycled into new products. Although the use of this method is relatively widespread, it is constrained by the fact that the physical and mechanical properties of the material tend to deteriorate during the recycling process. In addition, not all plastics are suitable for this form of recycling, and even if the materials are identical, their melting

points differ due to the presence of additives and degradation. To recycle materials, the same thermal melting conditions are required, and in some cases, material recycling is not possible [5]. Second, chemical recycling is a method whereby plastics are chemically decomposed and reused as raw materials. Specifically, techniques such as hydrogenolysis, hydrolysis, methanolysis, and glycolysis are employed. This method can also be applied to plastics that cannot be processed through material recycling; in addition to the high costs associated with chemical recycling, however, there are many technical challenges to its practical application, such as varying chemical stability contingent on the presence of additives and degradation [6]. Lastly, thermal recycling is a method of recovering energy through the combustion of plastics. Specifically, techniques such as pyrolysis, gasification, and combustion are employed. Thermal recycling is characterized by the advantage of high energy recovery efficiency; however, its environmental impact, such as carbon dioxide (hereinafter, CO_2) emissions generated during the combustion process, presents a major concern [7]. In Japan, the above three methods are primarily employed, and in 2022, the total amount of plastic emissions in Japan reached 8.23 million tons, with an effective utilization rate of approximately 87%. The remaining unused waste plastic accounted for the remaining 13%. In terms of effective utilization, material recycling accounted for roughly 22% of total waste plastics, with chemical recycling accounting for roughly 3% of the total and thermal recycling (heat recovery) accounting for roughly 62% of the total [8]. In the EU, in contrast, the definition of "recycling" refers to material recycling and chemical recycling and does not include the thermal treatment of waste [9]. Despite this contrast, thermal treatment of waste is currently practiced in several EU countries [10]. When considering different recycling methods, material and chemical recycling should be promoted over thermal recycling. Material recycling in particular has a significant impact on production costs, as additives and other materials must be added as the raw material is degraded [11]. Naturally, product quality must be ensured even for recycled products. Plastics recovered as raw material need to be separated into single materials. At present, plastic materials can be identified using near-infrared (hereinafter, NIR) light [12]. However, plastics identified and classified using NIR light exhibit different degrees of degradation. Recycled plastics made from plastics with different degrees of degradation must be quantitatively measured to determine the degree of degradation, as it is difficult to maintain a constant level of purity. In other words, it has to be determined whether the material is suitable for material recycling. Therefore, both the identification of materials using NIR light and the analysis of the degree of degradation can be used to produce suitable recycled materials and contribute to a sustainable, recycling-oriented society.

Plastics comprise polymers with moldable properties; at present, the most commonly used types of plastics are polyethylene (hereinafter, PE) and polypropylene (hereinafter, PP), followed by polyvinyl chloride (PVC), polyethylene terephthalate (PET), polystyrene (PS), and polyurethane (PUR) [1]. Developing countries also face challenges regarding plastic waste that is inadequately processed; as PP and PE materials degrade, they become a breeding ground for mosquitoes due to their high water absorption. Mosquito outbreaks can lead to the spread of infectious diseases [13]. Furthermore, even if discarded plastic is collected properly, it eventually ends up in landfills because there is no way to identify it and measure its degradation. Plastic waste that is left in outdoor environments can be washed into the ocean by wind and rain, resulting in marine plastic pollution [14]. Solid plastic waste that has drifted ashore is often unsuitable for material recycling when it has undergone severe degradation [15]. Therefore, in this study, samples of PP and PE were prepared from demographically degraded plastics, and the degree of degradation was determined using the terahertz (hereinafter, THz) wave region as opposed to the NIR spectrum. In recent years, THz measurements have become more accessible as they are

used in widely available devices such as car radars [16]. If the vibrational spectrum in the terahertz range can be used to identify fingerprint regions and determine degradation, it is possible that the above problems could be solved.

2. Previous Research

THz waves are used not only in the field of telecommunications but also in the non-destructive testing of infrastructure, such as concrete and electrical wires [17–19], and the quality assessment of plastics [20]. They are also used in the field of plastic identification [21]. In a previous study examining the use of THz wave identification methods for plastic materials, Zhang et al. reported the non-destructive identification of plastic pellets through THz time–domain spectroscopy (hereinafter, THz-TDS) [22]. Specifically, absorbance spectra were measured using THz-TDS, and seven types of plastic pellets were identified as materials through machine learning analysis. A discrimination accuracy of 95.7% was achieved by investigating possible synergies of combining machine learning with THz spectroscopy. At present, recycling plants operate equipment that uses near-infrared light as a probe to identify waste plastic materials. However, black plastic absorbs NIR light to a large extent, and transparent plastic transmits NIR light to a large extent as well, making it difficult to detect the reflected waves necessary for identification, and thus, the use of THz waves could make it possible to identify materials [23]. Thus, research is also being conducted to collect recycled materials and transform them into commercialized products [24]. Furthermore, in the identification of PP and PE, researchers investigated the practical application of PP and PE material identification in waste plastic bottle caps [25]. The investigation was based on spectral information obtained from a gallium phosphide (hereinafter, GaP) THz spectrometer able to sweep frequencies from 0.5 THz to 7 THz, and a sub-THz instrument has been developed that uses small and inexpensive semiconductor electronic devices at specific frequencies below 0.14 THz to differentiate different types of waste plastics [26]. As the employed sub-THz band devices are compact and pose no harm to the human body, the constructed devices can be transported from the laboratory to public environments to obtain measurements and be adopted. Furthermore, THz waves have been used to identify materials such as plastic containers and clothing [27,28].

Commercial instruments used for THz spectral measurements include THz-TDS, which uses the aforementioned femtosecond ultrashort white pulses, and Fourier transform infrared spectrophotometers (hereinafter, FTIR), which use ceramic heaters or mercury lamps with high intensity in the far infrared region as light sources [29]. FTIR is typically used for molecular vibrational analysis; THz-TDS enables time–domain measurements of amplitude and phase information.

The measurement bandwidth depends on the type of antenna employed, ranging from low frequencies below 100 GHz for bow-tie antennas to high frequencies above 3 THz for dipole antennas. Furthermore, in recent years, systems have been developed that enable spectral measurements by frequency sweeping a monochromatic source of THz waves generated from GaP or Lithium Niobate ($LiNbO_3$) optical crystals based on nonlinear optical effects (difference frequency mixing), and to obtain a spectrum with high frequency resolution while avoiding the use of Fourier transform, it is necessary to use a light source with high frequency purity [30].

High-resolution and broadband measurements enable not only the structural analysis of crystal polymorphs but also the detection of lattice defects that occur in crystals and the quantitative evaluation of residual trace impurities on the ppm order, which are conventionally difficult to detect. A database by Shizuoka University, which also includes X-ray diffraction (hereinafter, XRD), is particularly suited for these measurements [31].

In addition, a number of studies on THz waves and degradation are discussed in the literature. Studies on the degradation of plastics have been conducted in a wide frequency range, from ultraviolet to THz. In particular, FTIR research involving the use of mid-infrared light sources has a long history, and analyses have been performed not only on existing plastics but also various types of samples such as environmental microplastics [32]; in addition, methods for analyzing plastic degradation from multiple aspects, including structure and shape analysis such as XRD and scanning electron microscopy (hereinafter, SEM), have also been reported [33]. Studies on degradation evaluation using THz waves have also begun to emerge, albeit gradually [34,35]; nonetheless, such analyses are carried out in combination with conventional methods such as FTIR [36]. Chemiluminescence, which enables the quantitative evaluation of oxidative degradation, is also beginning to be reported as a new evaluation method [37].

The frequency of THz waves corresponds to the frequency of vibration of the molecular chains that constitute the polymer [38], and the dielectric constant in the THz band of plastics is closely related to the mass of the molecular chains, as it is based on fluctuations in molecular chains, the basic backbone of the material, as discussed in previous studies [39,40]. The dielectric constant is also impacted because the vibrations among the molecular chains are altered by the cleavage of the molecular chains due to ultraviolet (hereinafter, UV) degradation and the increase in the mass of the molecular chains due to oxidative degradation, in addition to being impacted by the type and amount of additives used, including plasticizers and antioxidants. Plasticizer is a generic term used for substances added to materials to provide them with flexibility and elasticity, commonly used in polymers such as plastics and rubber. The addition of a plasticizer may soften the material, making it easier to mold and process. Spectroscopic information in the THz band, which corresponds to the number of vibrations among molecular chains, can provide information on changes in the fluctuations in the said chains. Spectroscopic information is obtained by dividing light into different wavelengths and frequencies, and it is sometimes used to analyze the properties and components of materials. To obtain this information, the wavelength to be measured is scanned, or a spectrometer is employed. In a spectrometer, light is split into wavelengths, and their intensities are measured to produce a spectrum. The spectrum is a graph showing which wavelengths of light a material absorbs, reflects, or transmits. The refractive index and absorption coefficient of plastics are generally proportional to their density; it should be noted, however, that some specific types of polymers may exhibit different behavior [41]. The reflectance and transmittance of THz waves on plastics can be used not only to identify materials based on the mass of their molecular chains [27] but also to analyze any changes in characteristics to determine the type and amount of additives used [42] and even their degradation state [27,43]. The refractive index of a material is the ratio between the speed of light propagating through this material and the speed of light in a vacuum. The absorption coefficient is the fraction of energy absorbed by a material per unit distance of the EM wave's propagation through a particular material. Container and packaging plastics and product plastics do not specify information on molding conditions, additives, and additive amounts, which are strongly correlated with molecular chain length. Molecular weight and additives can be analyzed; however, such processes require not only time but also considerable cost. Considering current prices in the field of plastics, it could be possible, without complex measurement and analysis, to simply measure the relative change in plastics molding under identical conditions, rather than absolute measurement of material identification and additives. Such efforts represent effective use of THz measurement in consideration of the current climate, as it does not require complex measurement and analysis procedures.

One of the most common causes of plastic degradation is oxidation reactions. Peroxy radicals (ROO·) generated by heat or UV-induced radicals react with hydrogen in the side chains of the molecular chain to form hydroperoxides (hereinafter, ROOH) and radicals. Further reactions by these radicals occur; as a consequence, the plastic becomes embrittled due to molecular chain scission caused by the decomposition of ROOH.

In Table 1, conventional degradation analysis methods are presented and described. The analysis of plastic degradation presents considerable challenges, and the degradation phenomenon is complex due to a variety of factors, not only heat and UV radiation. Other variables involved in this process include environmental factors, the heterogeneity of reactions, additives, and other factors, with no method currently available to elucidate the degradation mechanisms of plastics [44]. In light of these challenges, the degradation of plastics is analyzed based on multiple perspectives, examining numerous analytical results.

Table 1. Methods employed for the analysis of degraded plastics.

Analysis and Evaluation Methods	Degradation Analysis Items	General Analysis Benefits	General Analysis Limitations
Fourier transform infrared spectroscopy (FTIR)	Molecular structure	• Non-destructive and rapid analysis [45] • Detection of specific functional groups [46]	• Limited to surface analysis (typically a few microns in depth) • Not suitable for bulk property or long-range interaction analysis [45]
Scanning electron microscopy (SEM)	Morphology	• Applicable to a wide range of materials (polymers, metals, ceramics, etc.) [47]	• Potential for beam damage or charging artifacts [48]
Differential scanning calorimetry (DSC)	Crystallinity	• Capable of measurements over a wide temperature range (−90 to 550 °C) • Modulated DSC (MDSC) enables the separation of complex thermal events [49]	• Overlapping thermal events may complicate interpretation [49]
Thermogravimetry (TG)	Pyrolysis	• Thermogravimetric analysis is a simple, convenient, and economical method to quantify the thermal degradation properties of the investigated materials [50]	• In multi-component systems or samples with complex reactions, the TG curve may overlap, making it difficult to distinguish individual reaction steps [51]
Chromatography (CG)	Additive extraction	• High sensitivity enables the detection of trace-level compounds in complex biological and environmental samples [52]	• For cultural heritage analysis, destructive techniques such as chromatography may not be suitable as they can damage samples [53]
Chemical luminescence (CL) Terahertz spectroscopy (THz)	Degree of oxidation Molecular chain	Under development	

3. Experiment Methodology

3.1. Samples

In this study, the samples used for the THz measurements comprised two types of olefinic thermoplastics, PE and PP, which are commonly used in plastic bags: PE as Low-

Density Polyethylene (hereafter, LDPE) and High-Density Polyethylene (hereafter, HDPE) due to differences in crystallinity, and PP as isotactic polypropylene (hereafter, iPP), the most commonly used form. Regarding the HDPE and iPP, the pellets were placed in a small heat press set at 200 °C, held at 20 MPa for 5 min, and then cooled in water; with regard to the LDPE, the heating temperature was set at 170 °C, with all pressure conditions being identical. The film thickness after molding was 0.028 mm for LDPE, 0.034 mm for HDPE, and 0.046 mm for PP.

3.2. Thermal Degradation

A dryer was used to thermally degrade the materials. The samples were placed in a dryer maintained at 120 °C for 7 days or 14 days. Based on Arrhenius' law and assuming that the degradation rate doubles with every 10 °C increase in temperature, thermal degradation at room temperature of 20 °C corresponds to a period of 20–40 years. The thickness of the HDPE film after the oxidation test was 0.036 mm. The thickness of the film material was chosen to ensure that the spectrum could be investigated without saturating the transmittance in FTIR measurements to check for local vibrations in the mid-infrared region, and the process of thermal degradation was chosen to suppress the appearance of the peak due to a carbonyl group (hereinafter, C=O) around 1715 cm^{-1} to the noise level. By applying this condition, we successfully suppressed the peak due to C=O around 1715 cm^{-1} to the noise level.

3.3. UV Degradation

UV degradation was performed by exposing the samples to UV radiation at a wavelength of 365 nm for 7 days. The samples were placed in water to prevent the temperature from rising, with the UV irradiation process corresponding to 132 days of outdoor exposure, calculated as a one-year outdoor exposure test of 464 h, which is the xenon lamp weathering test period detailed in the Japanese Industrial Standards. The film thickness after UV irradiation was 0.029 mm for LDPE and 0.052 mm for PP. During the UV degradation process, the UV irradiation conditions are such that the appearance of the peak attributed to C=O at around 1715 cm^{-1} is kept at a noise level.

4. Measurement Methods and Equipment

4.1. Fourier Transform Infrared Spectrophotometry (IRAffinity-1S)

FTIR (IRAffinity-1S: Shimadzu Corporation, Kyoto, Japan), the most commonly used conventional degradation analysis method, was employed as a degradation indicator. The aim of this method is to measure transmission. The apotizing function was HappGanzel, the number of integrations was 64, the resolution was 4 cm^{-1}, and the measurement range was 400 cm^{-1} to 4000 cm^{-1}. Measurements were taken three times for all samples, and spectral changes were investigated.

4.2. Terahertz Spectrophotometry (VIR-F)

A portable FTIR device (VIR-F: JASCO Corporation, Tokyo, Japan) was used to obtain absorption spectra in the THz region. The measurement conditions were as follows: resolution of 4 cm^{-1}, totalization frequency of 256 times, and measurement range of 40 cm^{-1} to 800 cm^{-1}. The transmittance was calculated by dividing the sample spectrum by the boundary of the background spectrum. The same sample was analyzed eight times.

5. Experimental Results

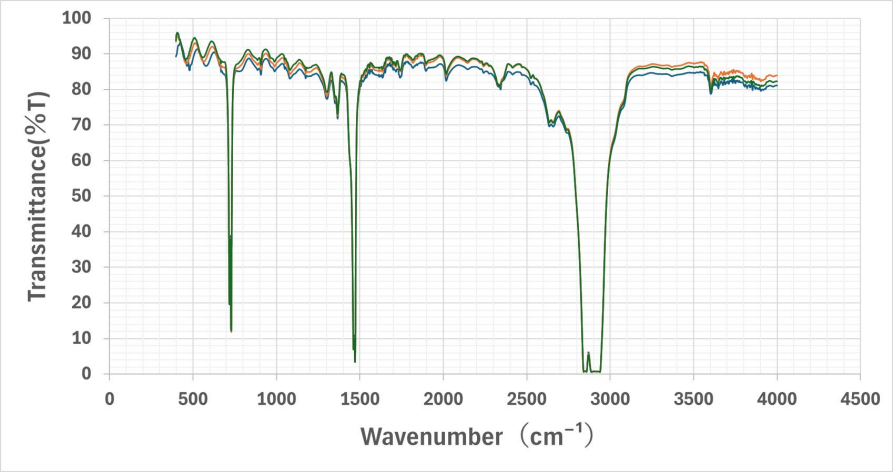
5.1. Degradation BASED on FTIR Results

5.1.1. HDPE

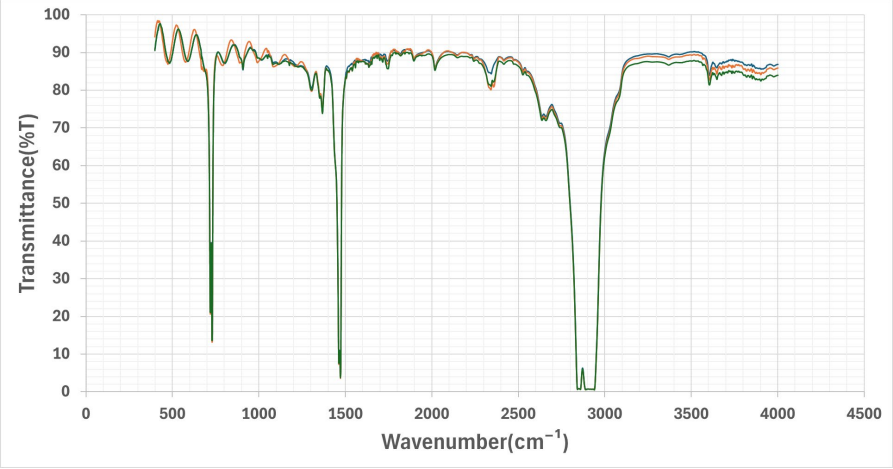
Our FTIR results show a large peak at 2925 cm^{-1} and 2850 cm^{-1}; however, it is not completely clear due to saturation occurring in the FTIR, where the spectrum cannot be measured because the thickness of the sample film makes it difficult for the spectrum to be transmitted to the sample. Two large overlapping peaks also appear at 1470 cm^{-1} and 1460 cm^{-1}, which are the peaks of the carbon–hydrogen bond (hereinafter, C-H) asymmetric stretching of the methylene group (hereinafter, CH_2) and C-H target stretching. These peaks are both C-H vibrations of CH_2.

Peaks can be observed at around 1369 cm^{-1} and 1300 cm^{-1}. Two large peaks appear at around 720 cm^{-1} and 730 cm^{-1}. These peaks are C-H transverse oscillations of CH_2 and are due to crystallinity, and in the case of HDPE, the peak at 730 cm^{-1} is larger than the peak at 720 cm^{-1}. The above are the characteristic peaks of HDPE. However, it should be noted that little variation was observed.

It is recognized that the C=O peak appears at 1715 cm^{-1} when organic materials such as plastics deteriorate. It is also recognized that a hydroxy group (hereinafter, O-H) peak appears between 2500 cm^{-1} and 3300 cm^{-1} due to degradation. However, only a small amount of the carbonyl group peak appeared during expansion, and almost no O-H was observed (Figure 1).



HDPE Undegraded sample

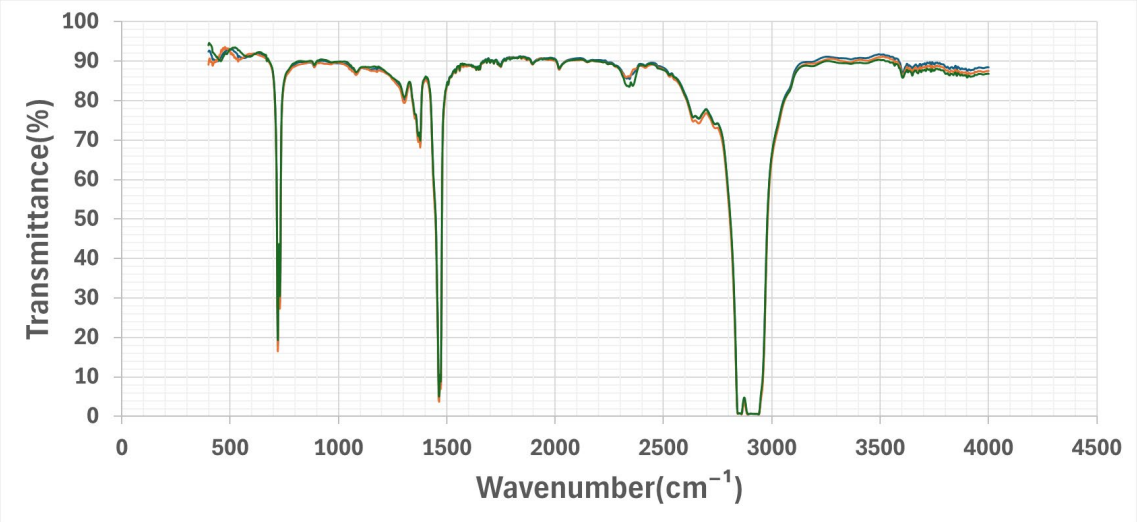


HDPE UV degradation 7 days

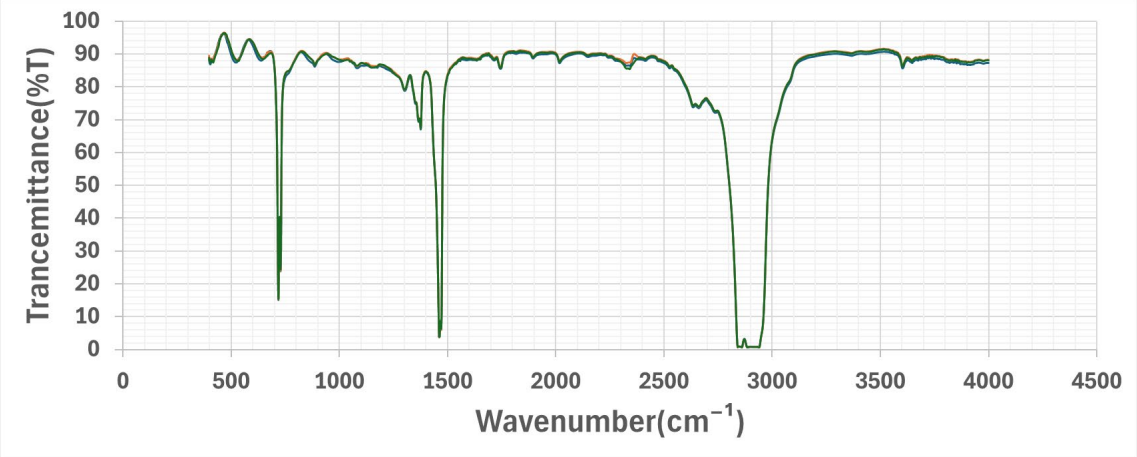
Figure 1. FTIR analysis results of HDPE.

5.1.2. LDPE

A PE-specific peak was also observed, similar to HDPE; the difference compared to HDPE is the fact that the peak at 720 cm^{-1} is lower and larger than the peak at 730 cm^{-1}, which is due to the lower crystallinity of LDPE than that of HDPE. The values of C=O and O-H were not large enough to be recognized as degradation; the other peaks in LDPE were likely due to the presence of additives or dissimilar bonds (Figure 2).



LDPE Undegraded sample

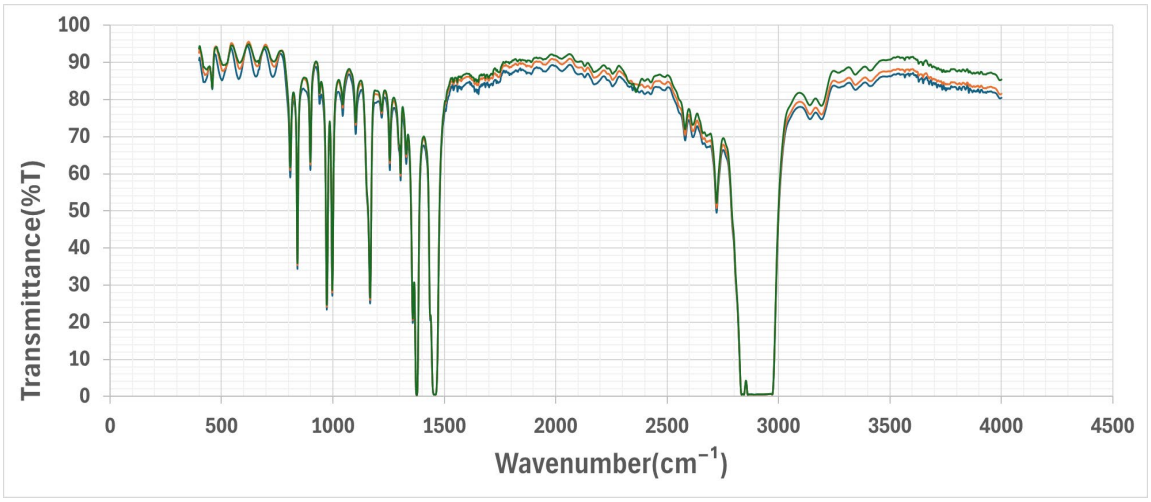


LDPE Thermal degradation 14 days

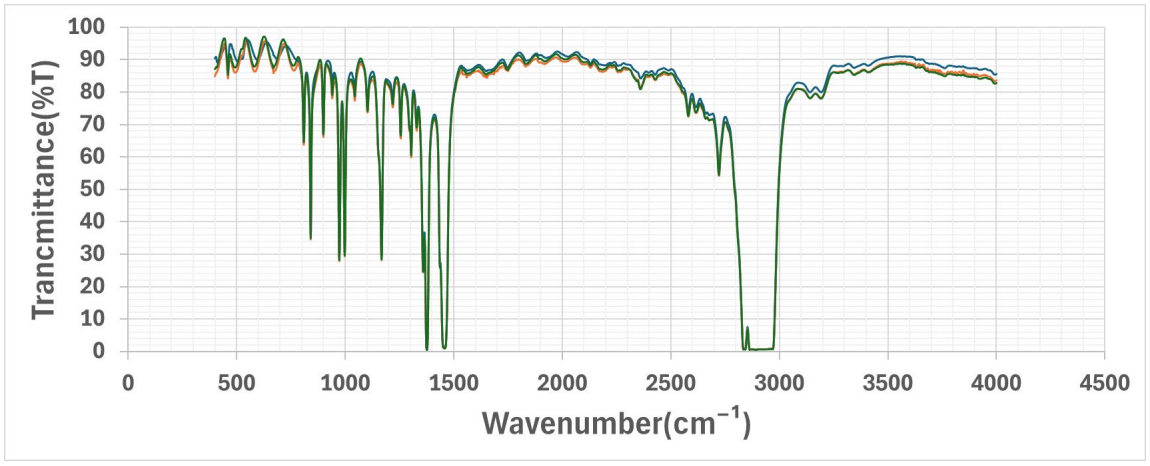
Figure 2. FTIR analysis results of LDPE.

5.1.3. PP

PP was saturated as in PE, but from 2830 cm^{-1} to 2975 cm^{-1}, considered to be CH stretching vibrations of alkanes; at 1462 cm^{-1} and 1377 cm^{-1}, the methyl group (hereinafter, CH_3) is an asymmetric variational vibration target of CH_3 at 1166 cm^{-1}, CH_3 transverse vibration at 997 cm^{-1}, and CH_3 torsional vibration at 997 cm^{-1} and peaks at 840 cm^{-1} and 898 cm^{-1}. Similarly, the C=O and O-H peaks appear in PP as a result of degradation; however, no significant peaks occurred after 7 days of thermal degradation (Figure 3).



PP Undegraded sample



PP Thermal degradation 7days

Figure 3. FTIR analysis results of PP.

5.2. THz Spectral Altimeter

5.2.1. Undegraded Sample

The spectrum of HDPE (undegraded sample) at 4–10 THz as a result of THz measurements is shown in Figure 4. Oscillations in transmittance due to the thickness and pseudo-refractive index of the film can be seen. If the thickness is known, the pseudo-refractive index can be estimated from the interference period. When the period is large, the value of the pseudo-refractive index becomes smaller. Conversely, when the period is small, the pseudo-refractive index becomes larger. The oscillations in transmittance are due to multiple reflections of THz waves in the film, and the amplitude (the difference between the maximum and minimum values) corresponds to the transparency of the film; the lower the absorption, the higher the amplitude. The transmittance in the spectrum can be affected by scattering due to distortion of the plastic sheet or irregularities on the surface, and the absorption of the plastic itself can be estimated based on the amplitude normalized by the median value (normalized amplitude).

$$\text{Amplitude} = (\text{Maximum} - \text{Minimum})/2 \quad (1)$$

$$\text{Normalized Amplitude} = [(\text{Maximum} - \text{Minimum})/2]/\text{Median} \quad (2)$$

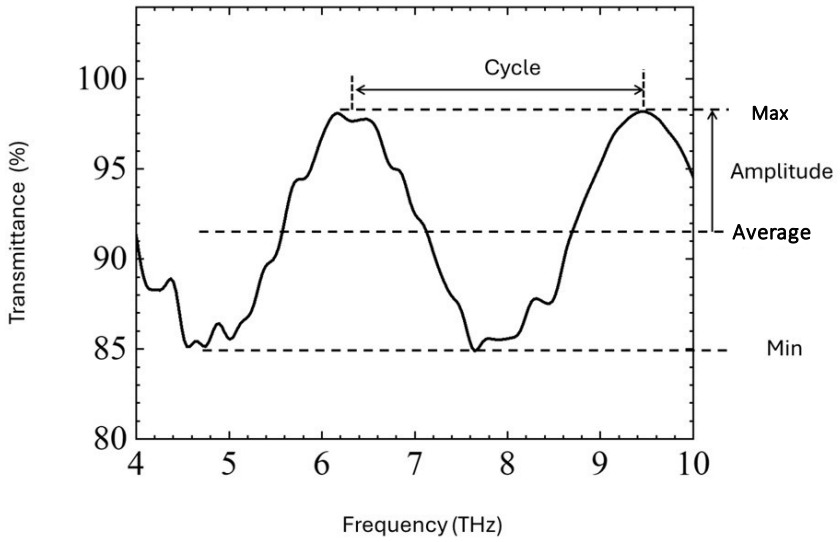


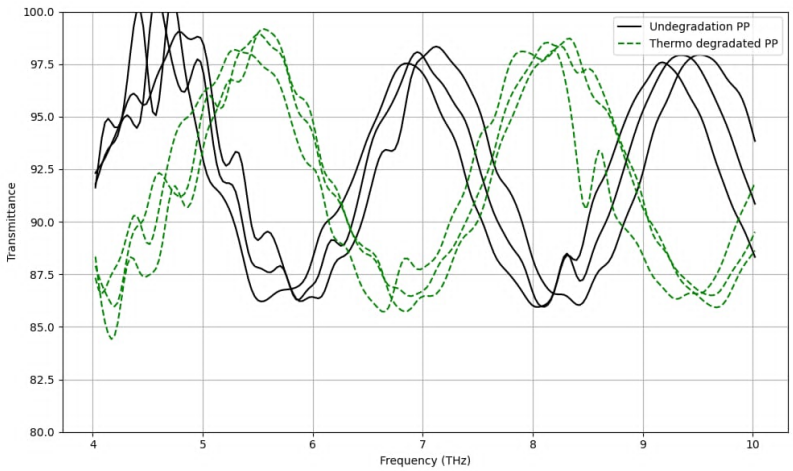
Figure 4. THz spectra of undegraded HDPE at laboratory temperature.

5.2.2. Result of Thermal Degradation

The refractive indices and normalized amplitudes of undecomposed LDPE and PP are 1.429 and 0.191, 1.344 and 0.154, respectively, and their values change to 1.470 and 0.183, 1.413 and 0.146 when thermally degraded under the above conditions. The increase in the pseudo-refractive index may be due to the increase in the polarity of the molecular chain, which is sensitive to THz waves, as a result of the addition of oxygen to the molecular chain during heating. The increase in polarity also increases absorption, resulting in a decrease in the normalized amplitude value.

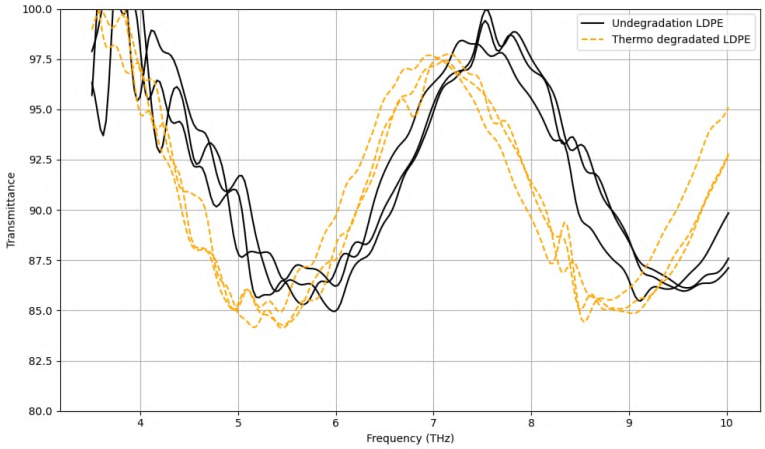
5.2.3. Result of UV Degradation

In Figure 5a, the measurement results are illustrated; in Figure 5b, the averages of the values for the undegraded, thermally degraded, and UV degraded samples are plotted and compared. The pseudo-refractive index and normalized amplitude of the undegraded HDPE are 1.374 and 0.244, respectively. The pseudo-refractive index and normalization amplitude of UV-irradiated HDPE are 1.432 and 0.233, respectively, showing similar changes to those observed for thermal degradation.

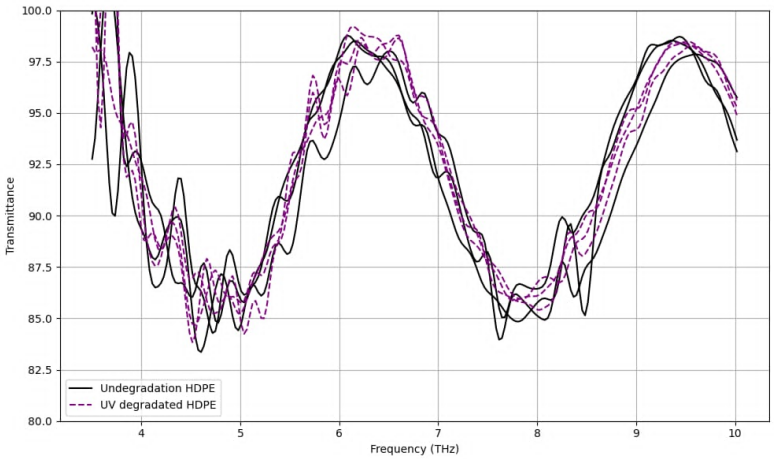


PP Undegradation and Thermodegradation

Figure 5. *Cont.*

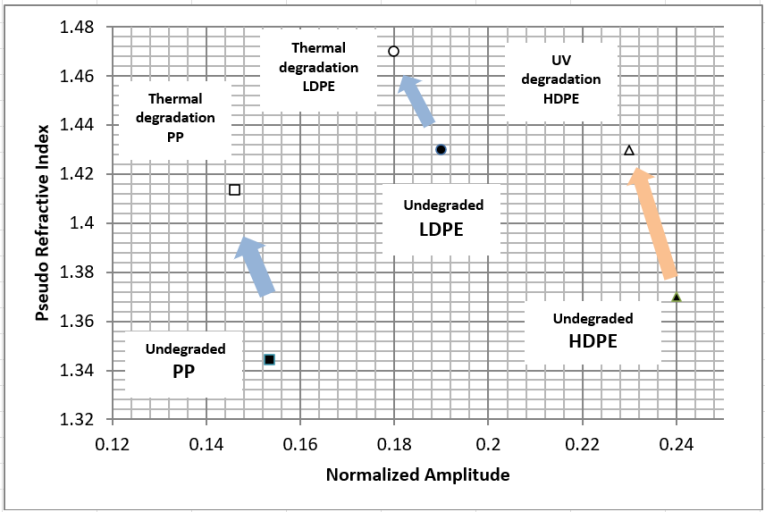


LDPE Undegradation and Thermodegradation



HDPE Undegradation and UV Degradation

(**a**)



(**b**)

Figure 5. (**a**) THz analysis results. (**b**) Pseudo-refractive indices and normalized amplitudes of thermally and UV-degraded plastic samples.

If UV irradiation only cleaved the molecular chains, no change in the normalized amplitude corresponding to absorbance would be expected.

However, the experimental results indicate a decrease. The precise details of the additives contained in the reagent pellets used in this experiment are unknown and cannot be discussed in depth; however, the increased absorption of THz waves suggests that oxygen adsorption at the cleavage sites increases both the pseudo-refractive index and absorbance.

6. Discussion

FTIR and THz spectrophotometers were used to evaluate undegraded and degraded samples of LDPE, HDPE, and PP. The results demonstrated clear differences between the undegraded and degraded samples in the THz spectrophotometer. The results showed that the normalized amplitude decreases as the sample deteriorates; in comparison, the pseudo-refractive index increases. The degree of degradation can be estimated using this result if data are available on an undeteriorated sample. We believe that evaluating the degree of deterioration of plastics can be applied in various contexts. For example, the extent to which the raw materials presented in plastic have deteriorated can be used as an indicator of whether the material can be recycled. In addition, it can also be used to evaluate plastics, for example, to determine whether plastic waste degraded by ultraviolet radiation, such as drifting plastic waste, should be recycled or subjected to treatment.

It may also have application value in determining the quality of raw plastics during the stage prior to use in products. Recycled plastics may contain minute deteriorations that are not visible on their surface and which may affect the performance of the final product. THz spectroscopy can be used to determine the degree of degradation, which could contribute both to the sustainable use of resources and to ensuring product reliability. In the future, a key challenge will be to investigate the effects of the properties of plastic materials and additives and to assess degradation with greater accuracy.

Another challenge in this regard is the fact that THz devices remain comparatively expensive. THz technology is now more widely available with the advancement of devices used in 5G and 6G advanced wireless communications and automotive applications. As such, the development of low-cost equipment using THz devices is also essential. Such equipment has the potential to influence the international approach to the recycling of waste plastics.

7. Conclusions

In this study, plastics such as HDPE, LDPE, and PP were artificially thermally and UV degraded, and corresponding changes were investigated using FTIR and THz spectrophotometers. No changes were observed when using the FTIR device. However, the THz spectrophotometer focused on two values of the samples: the “pseudo-refractive index” and the “normalized amplitude”. As a result, the pseudo-refractive index increased, and the normalized amplitude decreased for both samples. By determining the changes in spectral shape observed by using THz waves in this experiment, the possibility of determining the level of plastic material degradation was confirmed. Polyethylene and polypropylene represent just two types of plastic, with there being numerous other types in existence. The present method is practical for these two types of plastic; however, for other plastics, a material database is required. It is also effective for plastics that do not contain metal powder, since permeability varies based on the structure of the molecular chain.

The determination of the degree of degradation facilitates the removal of degraded plastics and ensures the quality of recycled pellets, which is particularly important as the demand for recycled materials continues to grow. In addition, the identification of degraded plastics can help prevent the formation of micro- and nanoplastics and contribute to the development of measures to solve current environmental issues.

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