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UV-Induced Degradation Behaviour of HDPE, PET and NBR Films: An FTIR Analysis

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Abstract
This study investigates the ultraviolet (UV) degradation behaviour of high-density polyethylene (HDPE), polyethylene terephthalate (PET), and nitrile butadiene rubber (NBR) under controlled UV irradiation at 254 nm. Chemical changes induced by photo-oxidation were analysed using Fourier Transform Infrared (FTIR) spectroscopy. The formation of oxygen-containing functional groups, particularly carbonyl and hydroxyl groups, was used as an indicator of degradation. Results showed that HDPE exhibited early- stage oxidation and increased brittleness, while NBR underwent moderate degradation involving both chain scission and crosslinking. In contrast, PET demonstrated minimal chemical and physical changes, indicating superior UV resistance. These findings highlight the strong dependence of UV stability on polymer molecular structure.

1. Introduction

Polymers have become an essential material in modern society due to their durability, low cost, and wide range of applications, such as packaging materials, consumer products, and laboratory applications. However, most polymers are resistant to natural degradation processes, leading to long-term accumulation in the environment. Ultraviolet (UV) radiation from sunlight is one of the main factors that initiates polymer degradation. UV exposure can cause photo-oxidative reactions by breaking polymer chains and generating free radicals. These reactions lead to chemical and structural changes. Over time, degraded polymers may fragment into smaller particles, contributing to environmental pollution. Different polymers exhibit varying responses to UV radiation depending on their chemical structure. High- density polyethylene (HDPE) is a widely used semi-crystalline polymer with a simple chemical structure composed of repeating ethylene units ($-CH_2-CH_2-$). Its semi-crystalline nature provides a balance between mechanical strength and limited elasticity. HDPE is characterized by a low degree of molecular branching, which results in high density (approximately 0.940 g/cm^3), high tensile strength, and good chemical resistance [1].

Polyethylene terephthalate (PET) is a semi-crystalline polyester synthesized through the polymerization of ethylene glycol and terephthalic acid. Owing to its strong chemical structure, PET is highly resistant to degradation and can remain in the environment for hundreds of years. However, exposure to solar ultraviolet (UV) radiation has been shown to promote the fragmentation of PET plastics in both terrestrial and aquatic environments [2]. PET is widely utilized in the manufacturing of beverage bottles due to its advantageous properties, including low weight, high mechanical strength, excellent optical transparency, and low permeability to carbon dioxide [3].

Furthermore, nitrile butadiene rubber (NBR) is a copolymer formed by acrylonitrile and butadiene monomers, which gives flexibility at low temperatures and oil resistance. Most nitrile rubbers have an acrylonitrile content between 19% and 40%; the higher the content is, the higher the resistance to hydrocarbons will be [4]. The degradation of polymer in the natural environment is initiated by photodegradation, followed by thermo-oxidative degradation [3]. UV light provides the energy needed for the incorporation of oxygen into the polymeric chain. Polymer breaks down into smaller polymeric fragments, which can eventually be metabolized by microorganisms in the surrounding environment [5,6]. During the process, polymer carbon is converted into carbon dioxide or biomolecules; however, complete degradation is extremely slow and takes up to 50 years [7].

However, comparative studies evaluating the UV degradation behaviour of different classes of polymers (thermoplastics and elastomers) under identical exposure conditions remain limited. FTIR is a valuable tool for measuring the changes in chemical bonds typical of microplastics ageing (carbonyl group, hydroxyl group, and carbon-oxygen). Infrared (IR) spectroscopy provides valuable information for evaluating polymer degradation by supporting the calculation of various weathering indices. The presence and growth of carbonyl groups (C=O) are significant, as these moieties act as key UV-absorbing sites that initiate and accelerate degradation reactions when polymers are exposed to ultraviolet radiation [8]. Therefore, this study aims to compare the UV- induced degradation behaviour of HDPE, PET, and NBR under controlled UV exposure using Fourier Transform Infrared (FTIR) spectroscopy and visual observation, to relate their degradation performance.

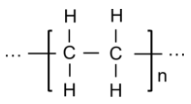
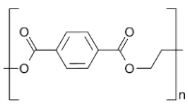
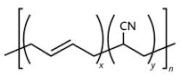
2. Materials and Methods

The instruments used in the analyses were a UV irradiation chamber equipped with UVA/UVB lamps and a Fourier Transform Infrared (FTIR) spectrometer with attenuated total reflectance (ATR) capability.

2.1 Materials

High-density polyethylene (HDPE) was obtained from used detergent bottles, polyethylene terephthalate (PET) from laminated paper materials, and nitrile butadiene rubber (NBR) from disposable nitrile gloves. Prior to analysis, the samples were thoroughly cleaned with distilled water, followed by ethanol to remove surface impurities. The materials were then air-dried at ambient conditions and cut into uniform sizes to ensure consistent and reproducible UV exposure.

Table 1 Characteristics of samples

Information	High-density polyethylene (HDPE)	polyethylene terephthalate (PET)	nitrile butadiene rubber (NBR)
Molecular formula	$(C_2H_4)_n$	$(C_{10}H_8O_4)_n$	$(C_4H_6)_x(C_3H_3N)_Y$
Structural formula			
Density (g/cm^3)	0.97	1.38	1.35

2.2 UV Exposure

The prepared polymer samples were exposed to UV radiation in a UV lamp to stimulate photo-ageing conditions. Samples were positioned at a fixed distance from the UV source to ensure uniform irradiation at 254 nm. The wavelength was selected to accelerate degradation; however, it does not fully represent the conditions of natural sunlight. UV intensity and exposure duration were controlled according to the experimental design, while unexposed samples were kept in the dark as controls. Temperature and humidity were maintained at constant levels throughout the exposure period (see Fig. 1).

Fig. 1 Samples before UV exposure using a Cole Parmer UV lamp

2.3 FTIR Analysis

After UV exposure, the chemical changes in the polymer samples were analysed using FTIR spectroscopy in the mid-infrared range (4000-400cm^{-1}) under ATR mode [9]. The spectra were recorded at selected exposure intervals and compared with those of unexposed samples. Variations in characteristic absorption bands, particularly carbonyl-related peaks, were used to assess the extent of UV-induced oxidative degradation. FTIR spectra were baseline-corrected and normalized to allow comparison of peak intensity changes.

Fig. 2 The polymers were analysed using Spectrum two, Perkin-Elmer, USA

3. Results and Discussion

3.1 Changes in the Appearance of Polymers

After continuous exposure to UV radiation at 254 nm for 24 hours, clear differences in appearance and physical characteristics were observed when the polymers were compared with their non-UV-exposed counterparts. These variations can be attributed to UV-induced degradation mechanisms such as photo-oxidation, chain scission, and crosslinking, which occur to different extents depending on the molecular structure of each polymer. The visual appearances of the samples are shown in Fig. 2. The non-UV HDPE sample appeared whitish and semi-opaque with a relatively smooth surface, retaining its original solid form and slight flexibility. In contrast, the HDPE sample subjected to UV exposure exhibited amore opaque and chalky surface with noticeable roughness. This suggests the occurrence of photo-oxidative degradation, where UV radiation induces polymer chain breakage, resulting in surface defects such as microcracks and embrittlement. Although significant discoloration was not observed, the UV-treated HDPE appeared duller than the untreated sample, likely due to increased light scattering caused by surface irregularities. From a mechanical perspective, the UV-exposed HDPE became noticeably more brittle and less flexible, consistent with chain scission and a reduction in molecular weight caused by UV irradiation.

Both UV-exposed and non-UV PET samples remained transparent and colourless, with no visible yellowing or surface damage detected after UV exposure. The UV-treated PET maintained a smooth surface and high clarity, indicating minimal visual degradation under the experimental conditions. The lack of noticeable colour change suggests that PET possesses relatively high resistance to short-term UV exposure, which may be attributed to the presence of aromatic rings that can absorb and dissipate UV energy, thereby stabilizing the polymer structure. Furthermore, no significant changes in stiffness or flexibility were observed, indicating that the bulk mechanical properties of PET were largely preserved after 24 hours of UV irradiation. In the case of NBR, the UV-exposed sample appeared slightly rougher and exhibited a mildly wrinkled surface compared to the non-UV sample. It also felt stiffer to the touch, suggesting the onset of UV-induced aging. These changes are likely associated with crosslinking reactions or chain scission occurring within the rubber matrix as a result of UV exposure. Although no obvious colour changes were observed, the reduction in elasticity indicates that prolonged or repeated UV exposure could eventually lead to cracking and a loss of mechanical integrity. Among the three polymers studied, HDPE showed the most significant visual and physical changes, particularly in terms of surface roughness and increased brittleness. NBR exhibited moderate changes, mainly affecting elasticity and surface texture without noticeable discoloration. In contrast, PET demonstrated the highest resistance to UV degradation, showing minimal changes in colour, transparency, and physical properties after 24 hours of exposure.

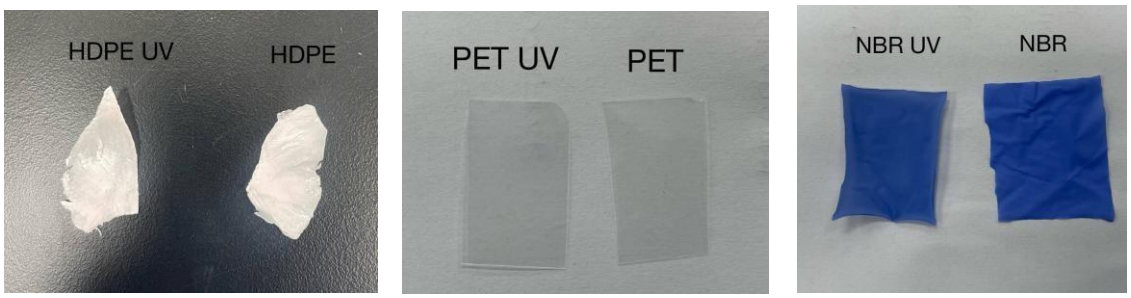


Fig. 3 Physical picture of the polymer with and without UV exposure

3.2 Chemical properties of polymers

3.2.1 FTIR characterization

FTIR was conducted to assess the changes in the functional groups of polymers. The results have been depicted in Fig. 4-6. For HDPE, both UV-exposed and non-UV-exposed samples displayed strong absorption bands at approximately 2915-2848 cm^{-1} corresponding to aliphatic C–H stretching vibrations of methylene groups, along with peaks near 1470 cm^{-1} due to CH_2 bending and around 718–729 cm^{-1} attributed to CH_2 rocking associated with crystalline polyethylene regions. These peaks confirm that the overall HDPE backbone remained intact after UV exposure. However, the UV-exposed HDPE spectrum showed slight reductions in transmittance intensity and minor peak broadening, particularly in the C–H stretching and bending regions, suggesting increased structural disorder within the polymer chains. Weak absorption features emerging in the carbonyl region (approximately 1700–1750 cm^{-1}) indicate the initial formation of oxidized species such as ketones, aldehydes, or carboxylic acids as a result of photo-oxidation. The formation of weak carbonyl absorption bands around 1700-1750cm^{-1} suggests the onset of photo-oxidation. In polymer degradation studies, the increase in carbonyl content is commonly evaluated using the Carbonyl Index (CI), which serves as an indicator of oxidation degradation. UV radiation initiates degradation by cleaving C–C and C–H bonds, which leads to the formation of free radicals that subsequently react with oxygen. Although the extent of oxidation is relatively limited due to the short duration of UV exposure, these changes are sufficient to account for the observed increase in surface roughness, loss of transparency, and increased brittleness in the UV-treated HDPE sample.

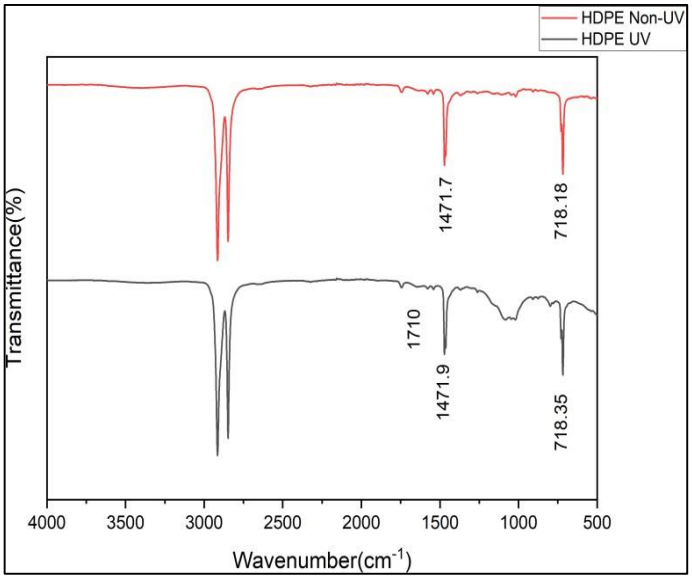


Fig. 4 Comparison of FTIR spectra of HDPE with and without UV exposure

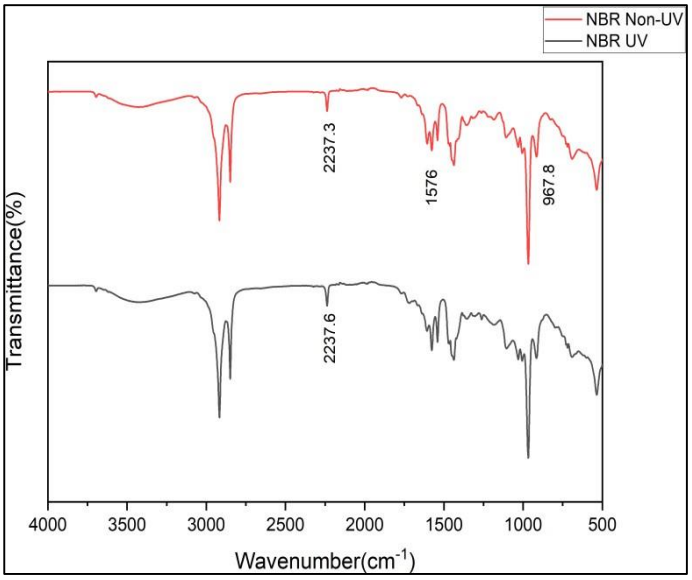


Fig. 5 Comparison of FTIR spectra of NBR with and without UV exposure

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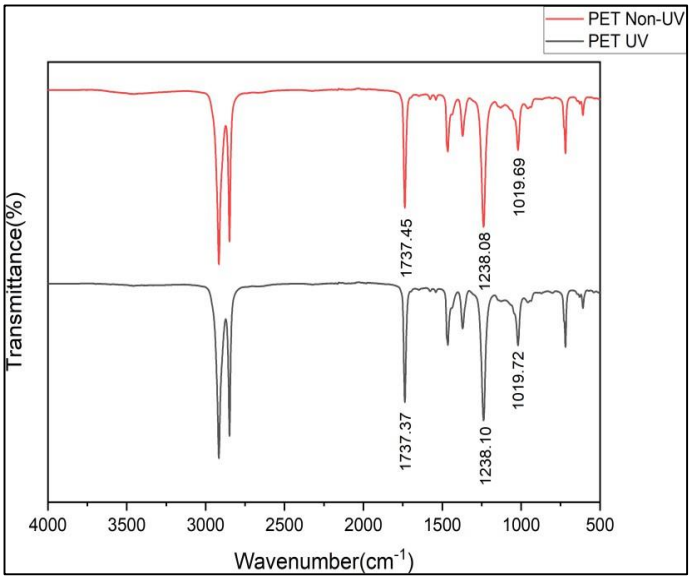

Fig. 6 Comparison of FTIR spectra of PET with and without UV exposure

Table 2 Key FTIR absorption peaks of polymer before and after UV exposure

Polymer	Wavenumber (cm-1)	Functional group	Observation after UV exposure
HDPE	2915-2848	C-H stretching	Slightly decrease in intensity
HDPE	1472	CH2 bending (scissoring)	Reduced intensity
HDPE	718	CH2 rocking (crystalline region)	Less sharp peak
HDPE	1710	C=O stretching (carbonyl)	Weak band and early oxidation
NBR	2237	CΞN stretching (nitrile group)	Slightly broadening and reducing sharpness
NBR	1540-1575	C=C stretching (butadiene unit)	Intensity decreased after UV exposure
NBR	967	=C-H out-of- plane deformation	Reduced intensity
PET	1735-1740	Ester C=O stretching	Slightly increase in intensity
PET	1238	C-O stretching (ester linkage)	Small intensity change
PET	1019	C-O-C stretching	Slightly variation

In comparison, NBR showed more noticeable spectral modifications after UV exposure, which can be attributed to its chemically unsaturated structure. Both untreated and UV-exposed NBR samples displayed a prominent absorption band at approximately 2237 cm^{-1}, corresponding to the nitrile (C≡N) group, along with characteristic peaks associated with aliphatic C–H stretching, C=C stretching, and deformation modes of unsaturated bonds. Following UV irradiation, variations in peak intensity and significant broadening were observed, particularly in the nitrile region and within the 1500–1600 cm^{-1} range related to C=C vibrations.

Furthermore, the fingerprint region between 1000 and 500 cm^{-1} became less distinct in the UV-treated sample, suggesting molecular rearrangement within the rubber network. These observations indicate that UV radiation predominantly affects the butadiene segments of NBR, resulting in concurrent chain scission and crosslinking reactions. While chain scission decreases molecular flexibility, crosslinking increases rigidity, which explains the reduction in elasticity and the slightly wrinkled surface appearance observed after UV exposure. The absence of prominent new oxidation-related peaks implies that the degradation remained moderate rather than severe.

Among the polymers investigated, PET exhibited the greatest resistance to UV-induced chemical alterations. Both UV-exposed and non-exposed PET spectra showed strong absorption bands around 1735 cm^{-1}, attributed to ester carbonyl stretching, as well as characteristic C–O–C stretching vibrations in the 1100–1250 cm^{-1} region and aromatic C=C stretching bands near 1500–1600 cm^{-1}. These features remained sharp and largely unchanged after UV treatment, indicating that the polymer backbone was well preserved. Only a slight increase in carbonyl peak intensity was observed, suggesting minimal photo-oxidation or limited ester bond cleavage. The absence of significant peak shifts or newly formed oxidation-related peaks indicates that the PET polymer backbone remained largely stable after UV exposure. This high UV resistance is mainly attributed to the presence of aromatic rings within the PET structure, which can effectively absorb and dissipate UV energy, thereby reducing photo-oxidative damage and stabilizing the polymer chains. This chemical stability is consistent with the minimal visual changes, as the PET samples maintained their transparency and smooth surface following UV exposure [10].

The FTIR results demonstrate that UV exposure at 254 nm for 24 hours induces polymer-specific chemical changes that depend strongly on molecular structure. HDPE, with its saturated aliphatic backbone, undergoes early-stage photo-oxidative degradation, leading to surface damage and embrittlement. NBR experiences moderate degradation due to its unsaturated bonds, involving both chain scission and crosslinking mechanisms that alter its mechanical behaviour [4]. In contrast, PET shows superior UV stability, with only minor oxidative effects detected. These findings correlate well with the physical and visual observations, confirming that polymers containing aromatic structures or more stable functional groups exhibit enhanced resistance to UV aging [11]. Overall, degradation resistance follows the order: PET > NBR > HDPE, with PET demonstrating the highest stability due to its aromatic structure, while HDPE is the most susceptible to UV-induced degradation.

4. Conclusion and perspective

This study demonstrates that UV degradation behaviour strongly depends on polymer structure. HDPE exhibited early-stage oxidation and embrittlement, NBR showed moderate degradation due to chain scission and crosslinking, while PET remained largely stable with minimal oxidative changes due to its aromatic structure. FTIR analysis supported these findings by revealing structural modifications corresponding to each polymer type. These findings highlight the importance of molecular design in improving UV resistance of polymer materials.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Zuhayra Mohd Zulfikar, Saliza Asman;* ***data collection:*** *Zuhayra Mohd Zulfikar;* ***analysis and interpretation of results:*** *Zuhayra Mohd Zulfikar, Saliza Asman;* ***draft manuscript preparation:*** *Zuhayra Mohd Zulfikar, Saliza Asman. All authors reviewed the results and approved the final version of the manuscript.*

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