

Article

Abiotic Degradation of Polymeric Personal Protective Equipment by Artificial Weathering

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Abstract

Personal protective equipment (PPE) like single-use face masks is discarded after a single use and poses a significant danger to the environment, resulting in plastic pollution. Most of the face masks are made from synthetic polymers and are non-biodegradable to the environment; hence, concerns are being raised about polymers' environmental impact. Most of the previous studies so far focus on polypropylene (PP) disposable masks and limited data related to environmental abiotic degradation behavior. There is a lack of studies aiming to understand the degradation behavior of different masks and the influence of physical-chemical factors. In this paper, we report on the environmental abiotic degradation of cloth, surgical and respirator filter facepiece 1 (FFP1) masks by accelerated artificial weathering. Furthermore, physical-chemical properties of masks were characterized by Fourier Transform Infrared Spectroscopy (FTIR), Differential Scanning Calorimetry (DSC) and Thermo Gravimetric Analysis (TGA). The cloth and FFP1 masks are made from polyethylene terephthalate (PET) and surgical masks were made from polypropylene (PP). Masks were exposed to an accelerated weathering test, which simulates the effects of natural sunlight and reproduces the damage caused by weathering elements such as sunlight, rain and dew. Masks were exposed to Ultraviolet radiation (UV) for 120, 240 and 360 h followed by condensation at 50 °C for 4 h. The FTIR results show that PET cloth and FFP1 PET masks are not degrading with the 360 h maximum exposure duration, which is equivalent to ± 180 days. The FTIR scan of the PP surgical mask after 120 h of exposure time shows that it was degraded and broken down into fragments. For the PET cloth mask, a 58% reduction in crystallinity and heat of enthalpy was observed after 120 h of exposure. UV exposure causes a chain scission reaction, breaking down the ester bond in the case of the PET cloth mask. In the case of the PET FFP1 mask exposed to UV for 120, 240 and 360 h, a drastic reduction in crystallinity was observed as compared to the neat (original) PET FFP1 mask. Neat PET cloth and FFP1 masks have higher onset and maximum degradation temperatures as compared to the 120, 240 and 360 h UV exposed masks. Neat PET cloth and FFP1 masks have better resistance to thermal degradation.

Keywords: artificial weathering; chain scission; degradation; environmental degradation; mask; personal protective equipment



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1. Introduction

Personal protective equipment (PPE) in the form of face masks, gloves and face shields plays an important role in the fight against transmissible diseases by acting as barriers,

as the main primary mode of transmission of the infectious virus, airborne particles, are transmitted through contaminated respiratory droplets from heavy breathing, coughing, sneezing and talking. PPE acts as a barrier by blocking particles from entering or leaving. The barrier reduces the chance of contracting or transmitting infectious particles. Wearing masks in public and practicing social distancing are important in preventing the transmission of infectious diseases. There was high consumption of these items, which resulted in increased waste disposal. PPE-like single-use face masks and gloves are disposed of after a single use and pose a significant danger to the environment, resulting in plastic pollution [1–3].

Synthetic polymers are widely used to make PPE, and commonly used fibers are polyester, polypropylene (PP), polyurethane and polystyrene. PP fibers are dominant textile fibers used in surgical, respirator filter facepiece 1 (FFP1) and N95 masks. In gloves, the dominant polymer is high-density polyethylene. Cloth masks are made of cotton, polyester or a blend of different fibers. Most face masks are made from different synthetic polymers, and these polymers take ages to degrade in the environment. Hence, there remains concern about polymers' impact on the environment. During the COVID-19 pandemic, it was estimated that around 4.3 billion masks and 2.17 million gloves were used every day. The use of individual masks and gloves is continuing in many places [2,4,5]. PPEs have been found in forests, rivers, oceans and streets. Less expensive PPE is more likely to be discarded than expensive PPE. Compared to other types of PPE, single-use masks and gloves have been found littered in public areas, beaches, shopping malls, parking lots, etc. Spennemann [6] reported that surgical masks (93.5%) are discarded more than N95 (1.6%) and cloth (4.2%) masks. It is estimated that about 250,000 tons of plastic are disposed of every day and only about 10–20% is recycled, 50–60% is sent to landfills and 20–30% is incinerated [7,8].

In many countries, the legislation encourages or forces communities to wear masks to minimize viral transmission; similar efforts are not seen when it comes to the environmental impact of these PPE when they are disposed of after use. Another problem with this slow degradation process is the release of micro- and nano-plastics impacting the environment as well as humans, as traces of them are seen in human cells and drinking water, leading to serious health concerns [9–12].

Physical and chemical degradation of PPE (PP face mask and low-density polyethylene gloves—LDPE) obtained from seawater under simulated environmental conditions for 60 days was reported (De-la-Torre et al., 2022) [13]. All experiments were performed outside of the laboratory and in environmental conditions from August to September 2021, with temperatures in August and September ranging from 34 to 40 °C and 32 to 38 °C, respectively. There was no rain during these two months at the place of study. The chemical structure of the materials was evaluated by Fourier Transform Infrared Spectroscopy (FTIR), X-ray diffraction (XRD) and scanning electron microscopy (SEM). Signs of physical degradation in PPE, such as ruptures and rough surfaces, were observed and increased as time progressed, along with changes in the PPE backbone. There were changes in the intensity of diffraction peaks, indicating shifts in the crystallinity of PPE and changes in the thermal behavior. Furthermore, there were traces of heavy metals like Molybdenum and Copper after degradation. The authors did not study the role of humidity and there was no information about thermal degradation.

In a study, Chou et al., 2025 reported the photolysis of PP face masks in facilitating manganese oxide nanoparticle formation in water surfaces [14]. They simulated water contamination as the face mask was in contact with water surfaces. The authors used a light intensity of $1.75 \pm 0.1 \text{ kW/m}^2$ for two weeks to stimulate photo aging and study the release of micro/nano-particles. The manganese oxide formed can alter the fate and transport of

pollutants like organic compounds and heavy metals and affect the quality of surface water. The authors reported changes in the FTIR spectra after photoaging, but there was no data about other physicochemical parameters, like thermal and chemical degradations.

In another study, Lyu et al., 2023 reported aging of disposable PP face masks in landfill leachates [15]. The masks consisted of three layers, spun-bonded inner and outer layers and a melt-blown middle layer. The UV weathering of the masks was performed in a UV chamber with a wavelength of 302 nm and a UV intensity of 20 mW/cm² at a distance of 0.5 inches. The duration of UV exposure was 4, 24, 36 and 48 h. The authors used FTIR and SEM for surface characterization and there was data related to the release of heavy metals. The authors reported that UV radiation caused oxidation and degradation in masks after UV exposure.

Yu et al., 2023 reported the weathering and degradation of polylactic acid (PLA) masks in a simulated environment for four weeks [16]. The authors reported that the weathering degradation of PLA fibers in water mainly occurs through the hydrolysis of ester bonds, leading to fiber breaking down and the release of microplastics. The exposure to UV light intensity was at 45 W, 254 nm and it was turned on every 12 h to simulate the day and night effect. The authors used FTIR for surface characterization but did not mention the weathering temperature used for the experiment. Furthermore, there was no information about chemical and thermal degradation.

Spennemann [17] reported environmental degradation of single-use surgical face masks under natural sunlight for 10 weeks and photographic images were taken as evidence every week. These masks were made-up of PP. Visible degradations were observed for the spun-bonded mask as compared to the melt-blown mask, with accelerated degradation observed in the spun-bonded mask after three weeks of exposure time. Knicker and Velasco-Molina [18] studied the degradation behavior of surgical face masks in soil for six months. The center of the mask degraded in 7 years, whereas the remaining sections degraded in between 19 and 28 years based on mean residence time in a carbon pool.

In another study, the degradation behavior of various types of face masks in an aquatic environment was studied [19] by using artificial weathering conditions for two weeks in substituted ocean water [19]. The authors used a UV lamp (UVA-340 nm) with an irradiance of 0.76 W/m². They used different characterization techniques to understand the impact of degradation. The chemical structures of the mask samples do not change drastically due to the shorter time used for artificial aging, which was only two weeks. Oliveira et al. [20] emphasizes the importance of understanding the degradation and toxicity of face masks and future studies are required to understand the degradation behavior of masks.

In a recent paper, De Bigault De Cazanove et al., 2025 studied the influence of artificial weathering on the abiotic degradation of LDPE films, of which many are used as plastic carry/shopping bags [21]. The main aim of this study was to show how different artificial weathering protocols affect degradation behavior. Authors used three different weathering protocols: continuous UV-A irradiation, cyclic UV-dark exposure and sequential UV-dark phase. The exposure to UV light was at 0.78 W/m² and temperatures were in between 50 °C and 60 °C. Authors highlighted the role of light in the degradation process and oxidative reactions continued during the dark phases. The authors did not mention duration and humidity was also not considered, which stimulates actual weather conditions. Furthermore, the degradation of film masks is not similar to that of fabric and nonwoven face masks.

From the summary of the existing literature related to the abiotic degradation of PPE, there are three major research gaps (Table 1). *The first gap* is the changes in the physicochemical parameters that describe changes in the material's structure and surface properties during the degradation phases that played an important role in environmental analysis.

How do physical-chemical parameters change after artificial weathering? *The second gap* is the types of PPE material used for degradation studies. The majority of the studies focus on PP and only a few studies focus on other fibers, as shown in Table 1. To address this, we have used cloth, surgical and respirator filter facepiece 1 (FFP1) masks, subjected them to artificial weathering and studied the environmental degradation behavior of masks. *The third gap* is the duration of degradation tests, and the influence of humidity/dew/rainwater simulating real environment and types of degradation testing (artificial weathering, in soil, natural sunlight, laboratory conditions). We have considered three different durations, 120 h, 240 h and 360 h for the abiotic degradation test. The 120 h accelerated test is approximately equivalent to 55–60 days of real conditions in South Africa. We have tested masks from 55 days (120 h) to 180 days (360 h) in the accelerated weathering chambers in the presence of humidity/dew/rainwater, simulating actual weathering conditions.

Table 1. Summary of the literature.

Authors	PPE Material	Duration of Degradation Test	Humidity/Dew/Rainwater CONSIDERATION	Degradation Testing	Characterization
De-la-Torre et al., 2022 [13]	PP face mask, LDPE gloves	60 days	No	Laboratory and in environmental conditions	FTIR, XRD, SEM. No information about thermal degradation.
Chou et al., 2025 [14]	PP face mask	14 days	Yes (sea water)	Artificial weathering, UV intensity: $75 \pm 0.1 \text{ kW/m}^2$	FTIR No information about thermal and chemical degradation.
Lyu et al., 2023 [15]	PP face mask	4–48 h	Yes	Artificial weathering, 302 nm and UV intensity: 20 mW/cm^2 at a distance of 0.5 inch	FTIR, SEM. No information about thermal and chemical degradation.
Yu et al., 2023 [16]	PLA face mask	30 days	Yes	Artificial weathering, UV intensity: 45 W, 254 nm.	FTIR No information about thermal and chemical degradation.
Spennemann [17]	PP face mask	70 days	No	Natural sunlight	Photographic images. No other information.
Knicker and Velasco-Molina [18]	PP face mask	180 days	No	Degradation in soil	Nuclear magnetic resonance (NMR) spectroscopy, microbial decomposition of masks.
Shen and Shi [19]	Polyurethane, polyester, nylon, silk and cotton masks.	14 days	Yes (sea water)	Artificial weathering, UV intensity: 0.76 W/m^2 , 340 nm	FTIR, XRD, SEM. X-ray photoelectron spectroscopy (XPS), contact angle.
De Bigault De Cazanove et al., 2025 [21]	LDPE films (not a part of PPE)	1 h, 23 h, 48 h	No	UV light was at 0.78 W/m^2 Temperatures: 50°C to 60°C	Degradation of a film is different to that of the face masks.

Most of the previous studies so far focus on PP disposable masks with limited environmental abiotic degradation behaviors. There is a lack of studies to understand the degradation behavior of different masks and the influence of physical-chemical factors. In this study, we report on the environmental degradation of cloth, surgical and respirator filter facepiece 1 (FFP1) masks by artificial weathering. Furthermore, physical-chemical properties of masks were characterized by FTIR, Differential Scanning Calorimetry (DSC) and Thermo Gravimetric Analysis (TGA).

2. Materials and Methods

2.1. Materials

In this study, three different face masks, cloth, surgical and FFP1 masks, were studied (Figure 1). The fiber compositions and physical properties of the mask are given in Table 2.

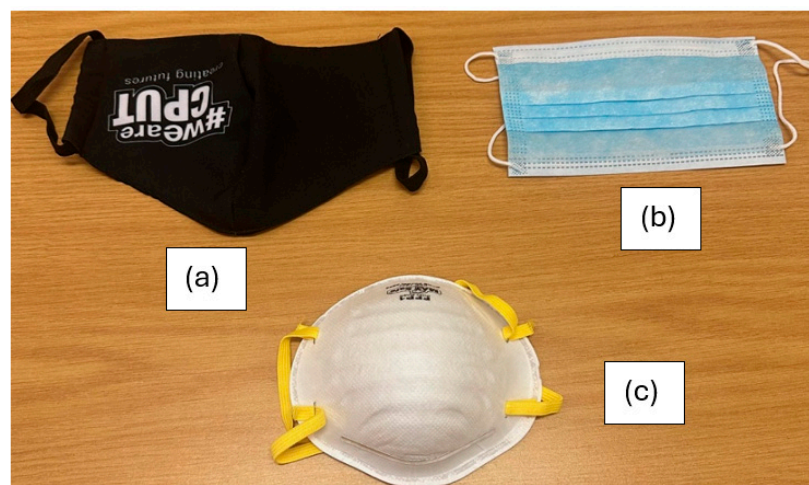


Figure 1. Different types of masks, (a) cloth; (b) surgical; and (c) FFP1.

Table 2. Mask specifications.

Sample Code	Sample Composition	Number of Layers	Thickness (mm)	Area Weight (g/m ²)
Cloth mask	PET	3	2.2	100
Surgical mask	PP	3	0.8	50
FFP1	PET	4	1.3	80

2.2. Environmental Accelerated Weathering Testing

QUV accelerated weathering testing chamber (from Q-Lab, Westlake, OH, USA) simulates the effects of natural sunlight and reproduces the damage caused by weathering elements such as sunlight, rain and dew. QUV exposure using UVA-340 lamps as per ISO 4892-3:2024 [22]. In this method, mask test samples were exposed to fluorescent ultraviolet (UV) radiation and water in an apparatus designed to reproduce the weathering effects that occur when materials are exposed in actual end-use environments to daylight, or daylight through window glass. In this test, the test cycles were carried out in two steps: step 1: exposure to UV light at 0.79 W/m² at 60 °C for 8 h; step 2: condensation at 50 °C for 4 h.

The experiment was performed for 360 h. The test materials were sampled after every 120 h of exposure for further characterization. To estimate the exposure time of the samples in the accelerated aging equipment that corresponds to the reported field period, the following considerations were made. The average solar radiation in South Africa is 16 MJ/m²/day [23]. In 230 days, the total radiation would be 3680 MJ/m². Of this total, 6.3% (231.8 MJ/m²) constitutes UV A type radiation (UVA), which is responsible for the UV photo degradation of polymers. To estimate the test time, the expected radiation (231.8 MJ/m²) was divided by the daily radiation supplied by the equipment (14.4 MJ/m²). In this test, the test sample exposure in a QUV accelerated weathering for 120 h is approximately equivalent to 55–60 days of real conditions in South Africa.

2.3. Characterization

2.3.1. Fourier Transform Infrared Spectroscopy (FTIR)

The FTIR technique was utilized to collect Infrared (IR) spectra of the test samples before and after environmental biodegradation. The total reflectance of the mask samples was analyzed on a PerkinElmer IR spectrometer (Shelton, CT, USA), which was obtained in the 500–4000 cm^{-1} range with 32 scans. After 120, 240 and 360 h QUV environmental weathering testing, test samples were taken for measuring the spectra. IR information of the samples was collected and processed with OMNIC software (version 9.0).

2.3.2. Differential Scanning Calorimetry (DSC)

Approximately 5–10 mg of test samples were weighed and analyzed in the temperature range of $-40\text{ }^{\circ}\text{C}$ to $200\text{ }^{\circ}\text{C}$ under a nitrogen atmosphere using DSC-8500 (PerkinElmer, Branford, CT, USA) for the determination of melting and cold crystallization temperatures, as well as corresponding enthalpies (ΔH 's). Each sample underwent three successive scans of heating, cooling and heating at a rate of $10\text{ }^{\circ}\text{C}/\text{min}$. Melting, crystallinity and heat of enthalpy of test samples were conducted before and after 120, 240 and 360 h of environmental degradation testing. The crystallinity is calculated by dividing the measured heat of crystallization or fusion by the heat of fusion for 100% crystalline PET [24] being 140 J/g and 207 J/g for PP [25].

2.3.3. Thermal Gravimetric Analysis (TGA)

The thermal properties of test samples were evaluated using TGA (Q600 TA Instruments, Eden Prairie, MN, USA). The samples (10–20 mg) were analyzed over a temperature range of 30 to $800\text{ }^{\circ}\text{C}$, at a heating rate of $10\text{ }^{\circ}\text{C}/\text{min}$ by using a nitrogen gas atmosphere. The thermal properties of the test samples were measured before and after 120, 240 and 360 h of environmental degradation testing to determine the changes in onset, derivative degradation, maximum degradation temperature and residue % (by weight) after $600\text{ }^{\circ}\text{C}$.

3. Results and Discussion

3.1. FTIR

The FTIR results of cloth, surgical and FFP1 masks before and after 120, 240 and 360 h of exposure to the environmental weathering chamber are shown in Figure 2. For the PET cloth mask, there were no significant changes in FTIR spectra as compared to the neat (original) sample for different exposure hours (Figure 2a). The intensities of C-H stretching wavenumbers at 3000–2850, C-H bend 1470 and C-H rock at 1383 and 728 cm^{-1} did not show any changes after exposure. These results show that PET samples are not degrading with the current exposure hours, where maximum exposure time (360 h) equates to ± 180 days. This can be attributed to the high ratio of cross-linked aromatic compounds as compared to the aliphatic compounds, making them resistant to UV degradation [26]. It is expected that the higher exposure of PET under environmental abiotic conditions may undergo chain scission, which leads to low molecular compounds. This mainly occurred at the carbonyl groups ($\text{C}=\text{O}$) at $1600\text{--}1800\text{ cm}^{-1}$, but the rate of degradation was mainly influenced by the physical-chemical factors of the PET materials in terms of molecular weight and highly cross-linked aromatic compounds [26].

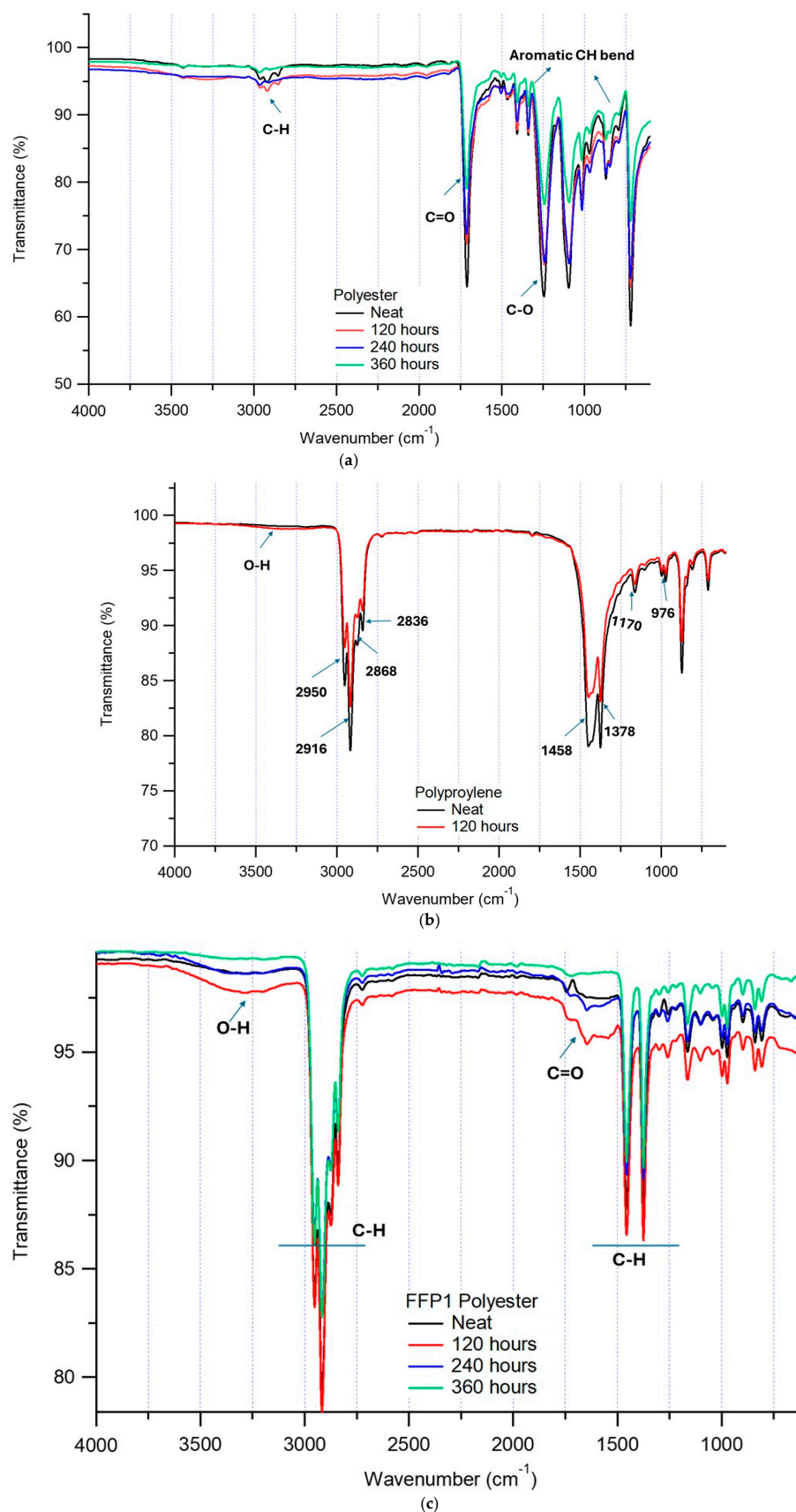


Figure 2. (a). FTIR scan of neat (original) PET cloth mask being subjected to different exposure times in the weathering test chamber. (b). FTIR scan of neat (original) PP surgical mask being subjected to different exposure times in the weathering test chamber. (c). FTIR scan of neat (original) FFP1 mask being subjected to different exposure times in the weathering test chamber.

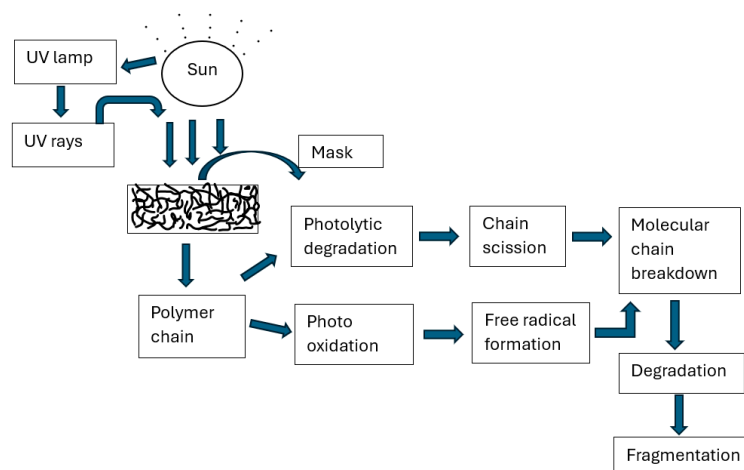
The FTIR scan of the PP surgical mask after 120 h of exposure time shows that it was degraded and broken down to fragments as compared to the neat mask (Figures 2b and 3). It was not possible to conduct further weathering tests after 120 h, as samples were already broken into powder form. FTIR results of fragmented samples showed increase in the peak areas of functional groups, such as hydroxyl ($-OH$) (wavenumbers $3200\text{--}3000\text{ cm}^{-1}$) and $C=O$ (wavenumbers $1600\text{--}1800\text{ cm}^{-1}$), due to the radical reaction with oxygen to form peroxy radicals. This radical reaction continues to abstract hydrogen from PP chains, creating hydroperoxides ($ROOH$) and new radical groups to form carbonyl derivatives like keto and esters [26,27].



Figure 3. PP surgical mask after 120 h of exposure in the weathering test chamber.

Due to this catalytic activity of the photo-oxidation process, PP surgical material becomes brittle and subsequent fragmentation occurred as shown (Figures 2b and 3). During these reactions, a more amorphous region is created as they are susceptible to oxygen and hydrolysis. During the photodegradation process, wavelengths above 290 nm in the UV region were absorbed by chromophores (or impurities). These chromophores release sufficient energy, resulting in chain scissions and formation of radicals that can either combine to form more chromophores or initiate photo-oxidation [27]. Due to the UV degradation, there are changes in the physical, mechanical and chemical properties of PP. On the other hand, there were no significant changes observed for the FFP1 mask, as compared to the neat sample for different exposure hours (Figure 2c). As compared to cloth masks, the functional groups of the FFP1 test sample showed a slight increase in the OH regions at $3000\text{--}3200\text{ cm}^{-1}$ and decreased intensity in the carbon groups at $1600\text{--}1800\text{ cm}^{-1}$ (Figure 2c). These results indicate that the test samples containing low molecular weight compounds of amorphous regions are degrading through the hydrolytic chain scission process [26,27].

The degradation mechanism of a mask subjected to artificial weathering is depicted in Scheme 1. The mask was subjected to artificial weathering in the QUV chamber. The constituent fibers in the mask and associated polymer chains of the fibers undergo photolytic degradation and photo-oxidation as a result of UV exposure. During the photolytic degradation process, chromophores or impurities in a material absorb UV light at wavelengths above 290 nanometers. This absorption of energy leads to the breakdown of polymer chains and the formation of free radicals. These free radicals can either combine to form more chromophores or initiate photo-oxidation. Since the amorphous region of a material is more vulnerable to oxygen, these degradation reactions predominantly occur there. UV exposure causes chain scission and breaks down the main backbone of the polymer chain. As a result, the mask was brittle, degraded and broken down into fragments [27,28].



Scheme 1. Degradation mechanism of a mask subjected to artificial weathering.

3.2. DSC

The DSC results of the neat PET cloth mask and mask exposed to 120, 240 and 360 h in the QUV weathering chamber are shown in Table 3. There is not much difference in the melting temperature (T_m), as shown in Figure 4a and the first cold crystallization temperature of the neat PET cloth mask and QUV exposed masks, Figure 4b. There was a 58% decrease in the crystallinity and heat of enthalpy after 120 h of QUV exposure. UV degradation breaks down the orderly polymer chain and induces defects in the molecular chain, resulting in lower crystallinity [28]. These changes indicate that more amorphous regions were created after exposure to UV light and causing chemical degradation in the material [29,30]. Exposure to UV causes chain scission and breaks down the ester bond, which is the backbone of the PET. It further affects by reducing molecular weight and forming more amorphous regions [31,32]. There is not much change in the 240 h QUV exposure as compared to the 120 h exposure. In the 360 h QUV exposure, there were further degradations in the mask samples, with further decreases in the crystallinity and heat of enthalpy. A different glass transition temperature (T_g °C) was observed for both the PET cloth mask and the mask exposed to different hours in QUV. This could be attributed to the different phase shifts in the material, with an initial higher T_g for the neat material and further reduction in T_g as there are continuous changes in the material phases.

Table 3. DSC results of the neat PET cloth mask and 120, 240 and 360 h QUV exposed masks.

Sample	Melting Temperature, Tm (°C)	Enthalpy, ΔHm (J/g)	First Cold Crystallization Temperature, Tcc1st (°C)	Glass Transition Temperature, Tg (°C)	%Crystallinity
<i>Neat PET Cloth mask</i>					
Outer layer	161.61	117.23	117.38	18.60	83.68
Middle layer				34.37	
Inner layer				1.98	
<i>120 h QUV</i>					
Outer layer	160.90	49.160	116.71	7.02	35.1
Middle layer				2.16	
Inner layer				2.86	
<i>240 h QUV</i>					
Outer layer	160.70	51.583	116.15	6.48	36.82
Middle layer				0.00	
Inner layer				0.00	
<i>360 h QUV</i>					
Outer layer	160.14	34.413	115.29	3.36	25.56
Middle layer				0.00	
Inner layer				4.70	

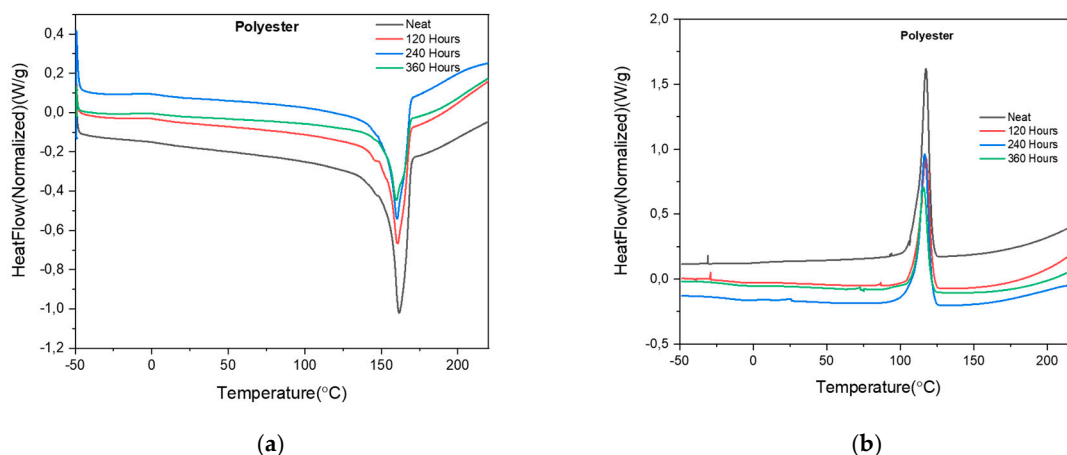


Figure 4. (a) DSC scan of PET cloth masks showing melting temperature, T_m (°C); (b) DSC scan of PET cloth masks showing first cold crystallization temperature, T_{cc1st} (°C).

The DSC results of the neat PP surgical mask and the mask exposed to 120, 240 and 360 h in the QUV weathering chamber are shown in Table 4. There is not much difference in the melting temperature (T_m) and first cold crystallization temperature (T_{cc1st}) of the neat PP surgical masks and the QUV exposed masks (Figure 5a,b), but a significant drop in the crystallinity (88%) and heat of enthalpy (88%) after 120 h of QUV exposure is observed and masks are brittle and fragmented, with some portions of the QUV exposed masks having disintegrated into powder form. The reason is due to both photolytic degradation and the photo-oxidation process happening in the amorphous region, causing chemical degradation (chain scission and free radical formation) in the material and breaking down the carbon-methyl backbone of the polymer chain [33,34]. The breaking down of molecular chains results in a significant decrease in molecular weight [31,32]. These results are similar to the FTIR result as explained in the previous section. Since there was a difference in crystallinity between the neat PP surgical mask and the 120 h QUV exposed mask, it led to different T_g (°C) in different layers.

The chemical degradation trends of the PET FFP1 mask and 120, 240 and 360 h QUV exposed masks are like that of the PET cloth mask (Table 5). The notable difference between them is the difference in crystallinity in the neat material which subsequently affects degradation behavior (Table 5). As the PET FFP1 masks were exposed to 120, 240 and 360 h in QUV, the reduction in crystallinity as compared to the neat mask is 48%, 56% and 90%, respectively. As a result of it, subsequent changes are observed in the T_m (Figure 6a,b); particularly, there was a drastic reduction in enthalpy at 360 h of QUV exposure.

Table 4. DSC results of neat PP surgical mask and 120, 240 and 360 h QUV exposed masks.

Sample	Melting Temperature, T_m (°C)	Enthalpy, ΔH_m (J/g)	First Cold Crystallization Temperature, T_{cc1st} (°C)	Glass Transition Temperature, T_g (°C)	%Crystallinity
<i>Neat PP surgical mask</i>					
Outer layer	160.27	49.846	124.7	5.27	24.08
Middle layer				3.03	
Inner layer				9.63	
<i>120 h QUV Powdered sample</i>	143.16	6.210	112.68	6.10	3

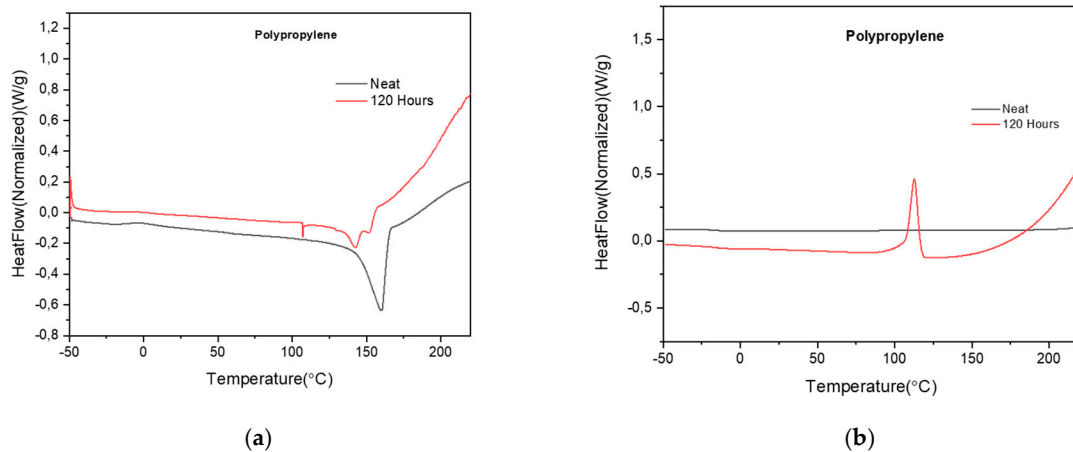


Figure 5. (a) DSC scan of PP surgical masks showing melting temperature, T_m (°C); (b) DSC scan of PP surgical masks showing first cold crystallization temperature, cold crystallization T_{cc} 1st (°C).

Table 5. DSC results of neat PET FFP1 mask and 120, 240 and 360 h QUV exposed masks.

Sample	Melting Temperature, Tm (°C)	Enthalpy, ΔHm (J/g)	First Cold Crystallization Temperature, Tcc 1st (°C)	Glass Transition Temperature, Tg (°C)	%Crystallinity
<i>Neat PET FFP1 mask</i>					
Outer layer	158.98	55.472	115.43	6.14	43.57
Middle layer				3.32	
Inner layer				11.71	
<i>120 h QUV</i>					
Outer layer	157.67	46.696	117.28	7.07	22.56
Middle layer				6.14	
Inner layer				2.11	
<i>240 h QUV</i>					
Outer layer	157.74	50.519	114.81	2.58	18.99
Middle layer				11.16	
Inner layer				6.36	
<i>360 h QUV</i>					
Outer layer	158.79	6.437	112.76	17.89	4.16
Middle layer				15.12	
Inner layer				0.00	

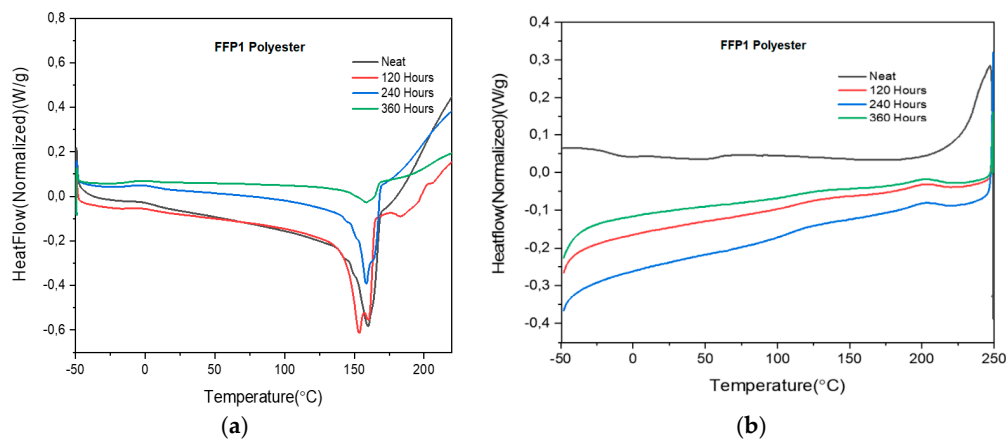


Figure 6. (a) DSC scan of PET FFP1 mask showing melting temperature, T_m (°C); (b) DSC scan of PET FFP1 mask showing cold crystallization, T_{cc} (°C).

3.3. TGA

The TGA results of neat PET cloth masks subjected to 120, 240 and 360 h are depicted in Table 6. The weight loss and TGA derivatives curves are shown in Figure 7a,b.

Table 6. TGA results of the neat PET cloth mask and 120, 240 and 360 h QUV exposed masks.

Sample	Tonset (°C)	Tmax (°C)	Residue wt.% @ 600 °C
PET cloth mask (Neat)	361.71	472.46	10.05
120 h QUV	397.71	469.52	23.81
240 h QUV	404.66	452.61	26.79
360 h QUV	402.12	454.36	26.00

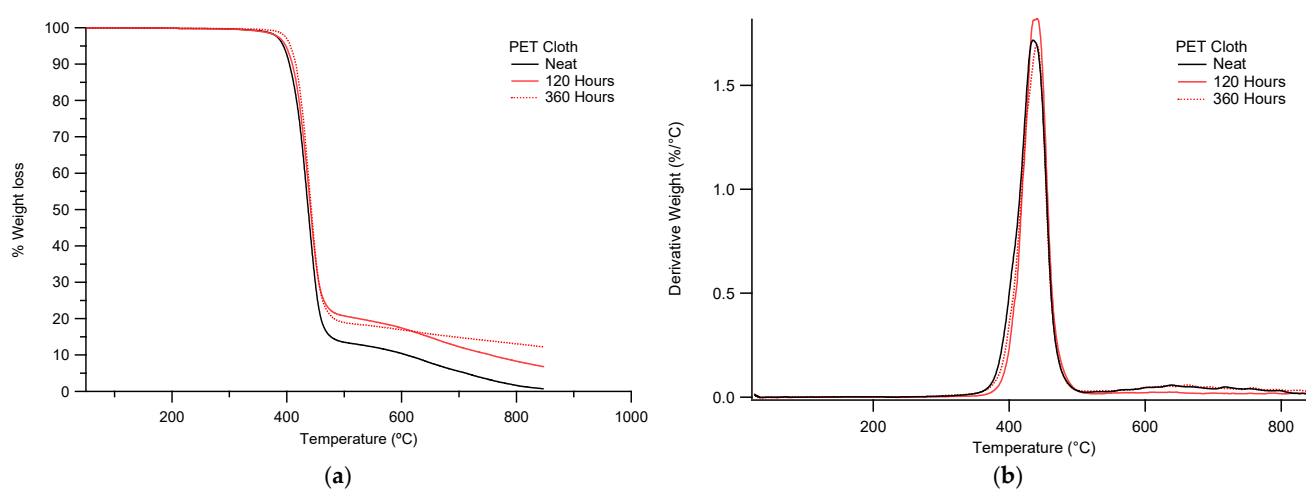


Figure 7. (a) TGA weight loss degradation behaviors of PET cloth mask before and after 120, 240 and 360 h of QUV exposure, (b) TGA derivative graphs of PET cloth mask before and after 120, 240 and 360 h QUV exposure.

The cloth masks TGA results showed higher Tonset temperatures of 361.71 °C, 397.71 °C and 404.66 °C, respectively, before and after 120 and 240 h of QUV exposure. The increased Tonset temperatures could be due to the degradation of low molecular compounds where minor amorphous groups were present (Table 6 and Figure 7a,b). The highest degradation temperatures of cloth mask showed decreases at 472.5 °C, 469.5 °C and 452.6 °C, respectively. These findings show that the bulk materials have undergone some hydrolytic breakdown. The cloth mask Tonset and maximum degradation temperatures, however, were nearly identical after 360 h of QUV exposure as opposed to 240 h. These findings show that the photo-oxidation process is hampered by the high ratio of cross-linked aromatic molecules (Table 6 and Figure 7a,b). The Derivative of the Thermo Gravimetric (DTG) curve and its peak height represent the rate of thermal decomposition at specific temperatures (Figures 7b and 8b). The PET cloth mask test sample after 120 h of QUV exposed testing showed a higher peak height at 400–500 °C as compared to untreated and 360 h QUV exposed test samples (Figure 7b). These results indicate that a higher rate of thermal decomposition occurs at 120 h QUV exposure due to the mass loss of amorphous groups of the PET cloth mask during the photo-oxidation process. On the other hand, after 360 h QUV exposure, derivative peak height is slightly lower than after 120 h QUV exposure, which indicates that after 120 h of QUV exposure test samples became crystalline groups more so than amorphous. It is known that amorphous groups undergo higher rates

of decomposition than crystalline groups. A similar degradation mechanism was observed for the PP surgical mask after 120 h QUV exposure (Figure 8a,b).

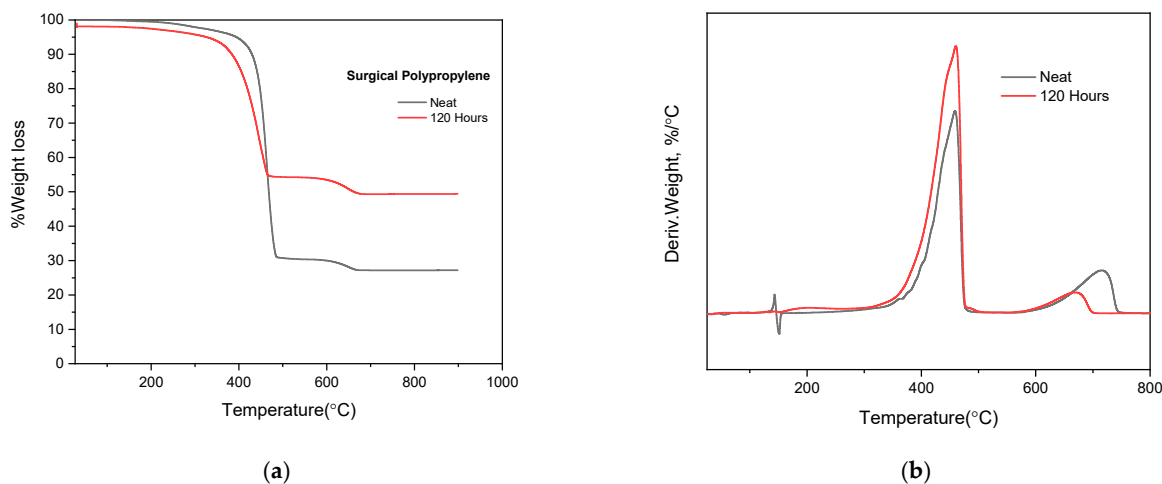


Figure 8. (a) TGA weight loss degradation behaviors of the PP surgical mask before and after 120 h QUV exposure, (b) TGA derivative graphs of the neat PP surgical mask before and after 120 h QUV exposure.

The TGA results of the neat PP surgical mask and 120 h QUV exposed mask are depicted in Table 7. As expected, the neat PP surgical mask has higher Tonset (°C) and Tmax (°C) temperatures as compared to the 120 h QUV exposed mask (Figure 8a,b) due to its higher crystallinity. It creates a stronger bond among the molecular chain and resists thermal degradation. Once masks are exposed to 120 h in QUV, there was a shift in Tonset (°C) and Tmax (°C) temperature values, resulting in lower temperatures due to the thermal degradation of the molecular chains [35]. At 600 °C, 32% residue (by weight %) was left in the case of a neat PP surgical mask and 55% residue was left in the case of 120 h QUV exposed mask. It can be attributed to the presence of additives or fillers in the PP polymer [36].

Table 7. TGA results of the neat PP surgical mask and 120 h QUV exposed mask.

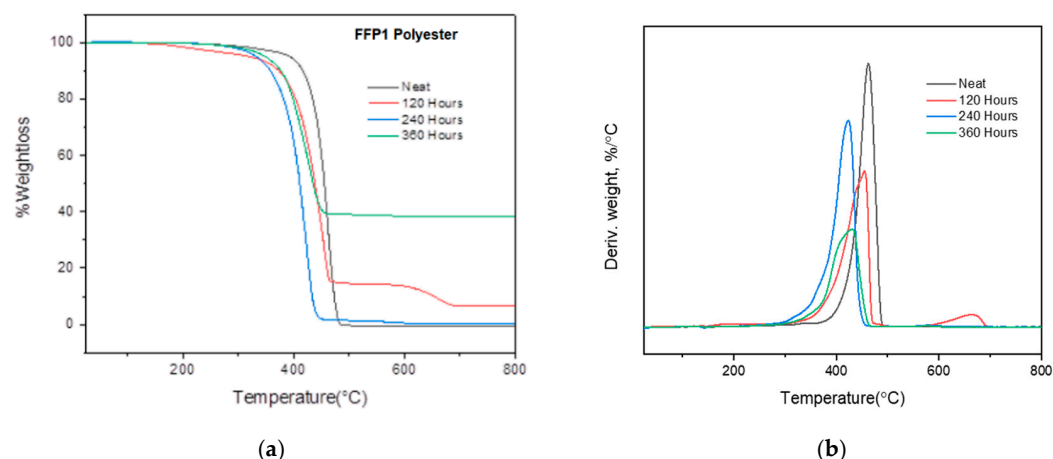
Sample	Tonset (°C)	Tmax (°C)	Residue wt.% at 600 °C
PP surgical mask (Neat) ^{NB}	382.43	464.40	32
120 h QUV	325.20	392.52	55

NB: The PP surgical mask sample had no layers after 120 h of QUV, as it was completely fragmented into powder. Therefore, it was not possible to radiate with QUV further for 240 and 360 h.

The TGA results of the neat PET FFP1 mask and 120, 240 and 360 h QUV exposed masks are depicted in Table 8. As compared to other PP and cloth mask test samples, neat PET FFP1 masks have higher Tonset (°C) and Tmax (°C) temperatures as compared to the 120, 240 and 360 h QUV exposed masks (Figure 9a,b) due to their higher crystallinity. As a result, neat PET FFP1 masks have better resistance to thermal degradation. After exposing masks to different hours in QUV, Tonset (°C) and Tmax (°C) temperatures decrease for all exposing hours due to chain scission, except Tmax (°C) for 360 h, which could be due to the presence of any additives/impurities [21]. At 600 °C, 5–18% residues (by weight %) were left in the case of the neat PET FFP1 masks and the 120, 240 h QUV exposed masks. About 55% residue left in the case of the 360 h QUV exposed mask, which could be attributed to the presence of additives/fillers in the polymer.

Table 8. TGA results of the PET FFP1 mask before and after 120, 240 and 360 h QUV exposure.

Sample	Tonset (°C)	Tmax (°C)	Residue wt.% @ 600 °C
PET FFP1 mask (Neat)	420.14	455.79	5.269
120 h QUV	391.01	440.57	18.161
240 h QUV	382.66	410.41	5.398
360 h QUV	375.38	420.71	40.489

**Figure 9.** (a) TGA weight loss degradation behaviors of the PET FFP1 mask before and after 120, 240 and 340 h QUV exposure, (b) TGA derivative degradation of the PET FFP1 mask before and after 120, 240 and 340 h QUV exposure.

4. Conclusions

Environmental degradation of cloth, surgical and FFP1 masks by accelerated artificial weathering was studied in this paper. The physical-chemical properties of the masks were characterized by FTIR, DSC and TGA. FTIR results showed that the PET cloth mask and the FFP1 PET mask were not degraded after 360 h of UV exposure, whereas the PP mask was degraded into fragments after 120 h of UV exposure. UV exposure causes a chain scission reaction and free radical formation, breaking down the carbon-methyl backbone in the PP mask. A drastic reduction in crystallinity was observed when comparing original PET FFP1 masks with FFP1 masks exposed to different UV hours. After 120 h of UV exposure, the PET cloth mask showed a 58% reduction in crystallinity and heat of enthalpy. Neat PET cloth and FFP1 masks have better resistance to thermal degradation.

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