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Radiation effect of polycarbonate films after electron beam irradiation*

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Polycarbonate (PC) is a promising material for high-absorbed-dose detection. In this study, the effects of electron beam irradiation on the optical properties and structure of PC were investigated. Colourimeter, ultraviolet–visible absorption spectrum, X-ray diffraction, gel permeation chromatography, and thermal stability analysis were used to characterise the properties of PC after different doses (0–1000 kGy) of irradiation. The results showed that the colour of polycarbonate turned yellow after irradiation and that there was a good relationship between the chroma value and the absorbed dose. Furthermore, the visible light transmittance, crystalline region, crystal size, weight-average molecular weight, and thermal deformation resistance of PC decreased with the increase in the absorbed dose. The thermal stability of PC was improved by irradiation. This study provides an important basis for developing PC into radiochromic dosimeter.

Keywords: Polycarbonate, Electron beam irradiation, Radiochromic dosimeter, Radiation effects

I. INTRODUCTION

The radiation effect of polymers has been widely investigated in recent years. Researchers have been trying to enhance the properties of polymer materials through ionising radiation, with the aim of making the modified polymers available in a wider range of applications [1, 2] . The chemical changes in polymers are small under moderate-dose irradiation. However, polymers are usually composed of thousands or even tens of thousands of monomer units; therefore, even small changes can significantly change the physical and chemical properties of the polymer. Generally, the modification of the polymer by ionising radiation depends on the structure of the polymer itself and the irradiation treatment conditions, such as the type of radiation, radiation energy, absorbed dose, dose rate, atmosphere, humidity, and temperature.

Polycarbonate (PC) plays an important role in polymers owing to its low production cost, heat resistance, easy processing, high impact toughness, high elastic modulus, creep resistance, and high optical transparency. It is widely used in the building materials industry, automobile manufacturing, medical instruments, aerospace, electronics industry, packaging, optical lenses, optical storage media, optical fibre manufacturing, and other fields [3]. The study of the radiation effect of PC has important theoretical and practical value. Numerous studies on PC have been conducted to elucidate the effect of varying absorbed doses on its thermoluminescence behaviour, degradation, optical density, and electrical, structural, and mechanical properties [4]. Abdul-Kader et al. (2018) investigated the influence of gamma irradiation (150–950 kGy) on the physical and chemical properties of Makrofol LT 6-4 nuclear track detector films. The results showed that the crystal size of PC changed after irradiation, and cross-linking and degradation occurred at specific doses. The band gap energy decreased, the dielectric constant increased considerably, and the intensity of photoluminescent spectral peaks decreased with increasing dose.

Zoul et al. (2020) found that by spectrophotometric measurement of irradiated PC samples, the optical density within the range of visible wavelengths could be relatively accurate for determining doses up to 200 kGy. The ability of PC to regenerate completely within a few months was also demonstrated at doses up to 30 kGy, and the positive effect of oxygen concentration on the rate of fading was confirmed [5]. Zoul et al. (2018) investigated the fading and annealing characteristics of radiochromic PC dosimeters [7]. Jaleh et al. (2007) used thermogravimetric analysis (TGA), Fourier-transform infrared (FTIR) spectroscopy, X-ray diffraction (XRD), and electron paramagnetic resonance (EPR) to identify the electron beam (EB) irradiation induced changes in the physical–chemical properties of PC [7]. They observed that the cross-linking probability of PC increased from 0 kGy to 50 kGy, and the decomposition temperature of PC decreased at high absorbed doses. The crystallinity of the polymer after irradiation did not change significantly, similar to that of unirradiated PC. EPR measurements revealed that an increase in the number of free radicals at higher doses was associated with faster decay due to an increase in the recombination rate. Chen et al. (2005) examined the effects of EB treatment parameters, such as different doses, dose rates, and dose classification, on the structure and mechanical properties of PC [8]. The results showed that the degradation of PC molecular weight was largely dependent on the dose. On the other hand, mechanical properties such as tensile strength and ductility were affected by temperature. Nouh et al. (2007) irradiated Makrofol detector samples with an EB dose of 10–400 kGy [9]. The physicochemical properties of unirradiated and irradiated Makrofol samples were studied by XRD, FTIR spectroscopy, colour difference measurements, and EPR. The results indicate that the Makrofol detector is a material that does not have a high resistance to degradation, and its tendency to cross-linking is much lower than that of several other solid-state nuclear track detectors.

Tang et al. (2014) used thermal analysis, XRD, and mechanical testing (tensile, hardness, wear, and impact proper-

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ties) to investigate the properties and structural changes in PC under EB irradiation at glass transition temperature (T_g) [10]. The T_g of irradiated PC sheet increased at about 10 kGy and then decreased at a high dose. Furthermore, within 70 kGy, the ordered structure of the amorphous phase of the sample was essentially the same. The wear resistance, hardness, and impact strength increased with the increase in dose, reached the maximum value at about 10 kGy, and then decreased with the increase in dose. The change in tensile strength was similar to that of impact strength, but the elongation at break dropped to half at 10 kGy. Under high-temperature irradiation, the molecules were rearranged under the synergistic effect of radiation and thermal migration. Therefore, the molecules were densely packed in the matrix, thus improving the properties of the material.

However, few studies have reported the radiation effect of PC in a wide absorbed dose range from the perspective of developing it into a radiochromic film dosimeter. Radiochromic films undergo chemical reactions after exposure to ionising radiation to produce significant colour changes, and this process does not require further processing by other methods such as thermal, optical, chemical, or amplification. The radiation chemical yield of chromophores is proportional to the absorbed dose. Therefore, the yield of chromogenic substances is first characterised by measuring the optical density or chroma before and after irradiation, and then the absorbed dose can be obtained.

Conventional dosimeters currently in use include calorimetric radiation dosimeters[11, 12], ionisation chamber dosimeters[13], chemical dosimeters (Fricke[14–17], dichromate[18], cerium sulfate[19], and solid dosimeters (radiochromic dosimeter[20–22], thermoluminescence dosimeter, radiophotoluminescence dosimeter[23]). Compared with other dosimeters, the radiochromic film dosimeter has the advantages of simple operation, convenient testing, high resolution, good response consistency, and direct reading, making it an ideal dosimeter for measuring gamma and EB-absorbed dose, electron accelerator field distribution, depth dose distribution and energy. It has wide application value in medical treatment, radiation processing, and other fields[24, 25]. Among all kinds of radiochromic film dosimeters, the FWT-60 film dosimeter produced by Far West Technology Company of the United States, which uses nylon as the base material and hexahydroxyethyl pararosaniline cyanide dye as the radiation-sensitive material, has the best dosimetry performance, and its dose measurement range is 1–200 kGy. The American Institute of Standards and Technology has designated the dosimeter as the standard dosimeter for radiation processing[26, 27]. The FWT-60 series of radiochromic film dosimeters has become the exclusive product of Far West Technology, which sells well worldwide. In the 1980s and 1990s, Chinese research institutions such as Guangdong Test Institute, Chemical Protection Research Institute, and Military Medical Science Research Institute carried out the development of radiochromic film dosimeters. Heretofore, it has not been applied and popularised because of small batch size and poor attention. At present, most of the domestic demand for radiochromic film dosimeters depends on imports. To break through this technical bottleneck, many research teams carried out the development of high-dose radiochromic film dosimeters. The research work mainly includes the following aspects: the dosimetry performance of FWT-60-00 radiochromic film dosimeter; formulation of radiochromic film dosimeter and scheme for mass production; new high-sensitivity radiochromic film electronic dosimeter and gamma dosimeter; proton irradiation effect and annealing effect of dosimeter; radiochromic film dosimeter for high-dose level absorption dose measurement; and the PVB-based low dose radiochromic film dosimeter. However, there are few studies on the radiation effects of radiochromic film materials that can potentially be used for wide-range and high-dose measurements.

In this study, the effect of EB irradiation with different doses (0–1000 kGy) on the optical and structural properties of PC films was investigated. The prime focus was on the colour, visible light transmittance, ultraviolet absorption, crystal structure, molecular weight, thermal deformation, and thermal stability of PC after irradiation. The methods of colourimeter, ultraviolet–visible absorption spectrum, XRD, gel permeation chromatography (GPC), and thermogravimetry (TG) were used for these analyses. The research results have theoretical significance for the study of radiation effects of polymers and have guiding significance for the application of PC in the field of high absorbed dose detection or as structural material in the field of high-dose irradiation.

II. EXPERIMENTAL DETAILS

A. Preparation of sample

The PC films in this study were manufactured by Jiaxing Diren Polycarbonate Co., LTD., Zhejiang, China, with a thickness of 0.3 mm and a density of 1.2 g/cm^3. The thickness of PC film is uniform. Its molecular formula is $(C_{16}H_{14}O_3)_n$[28]. The physical and chemical properties of PC films are as follows: the linear expansion rate is 3.8×10^{-5} cm/°C, the thermal deformation temperature range is higher than 135 °C and lower than -45 °C, and the light transmittance is 90 % ± 1 %. The PC films were cut into square (20 mm × 20 mm × 0.3 mm) and put into the sample box for subsequent use.

B. EB irradiation

The irradiation facility used in this study is the electron accelerator (IS1020) of Xianghua-Huada Biotechnology Co., LTD., Hunan, China. The energy and power of the electron beam are 10 MeV and 20 kW, respectively. The sample boxes were placed on a conveyor belt, and the samples traversed under a scanning horn several times to receive a desired dose. The PC films were irradiated with 0, 50, 100, 200, 400, 600, 800, and 1000 kGy. Irradiation was carried out at room temperature and in an air atmosphere, and the absorbed dose was traced by a silver dichromate dosimeter. The dose rate was 10

kGy/s corresponding to 50 kGy per pass. The analyses were performed immediately after irradiation.

C. Chroma analysis

The International Commission on Illumination (CIE) XYZ colour space comprised all colour sensations that people can experience. It serves as a standard reference for many other colour space definitions[29]. The CS-5960GX colorimeter was used to analyze the chroma of irradiated PC films. The lighting source is an all-band balanced LED light source (CLEDs), and the sensor was selected as a dual optical array sensor. The measured wavelength ranges from 400 nm to 700 nm, with an interval of 10 nm.

D. Chroma value fading characteristic

It is necessary to study the fading characteristics of PC, a radiochromic material, to develop it into a radiochromic dosimeter. The PC films irradiated with 200, 600, and 1000 kGy were stored in a light-blocking box, and their chroma values were analysed at days 0, 2, 5, 10, 20, 30, and 60 to determine the change in chroma values with time.

E. UV-visible absorption spectra analysis

The absorption spectra of pristine and irradiated PC films were recorded using a UV-3600 spectrophotometer. The light source of the spectrophotometer was set to an automatic mode with a conversion wavelength of 310 nm and a slit width of 2 nm. The test wavelength range was 200–800 nm, with a resolution of 0.1 nm, a step size of 0.5 nm, and a medium scanning rate. The PC films were sandwiched at the centre of the sample clip and placed in the same test position to minimise optical path errors.

F. XRD Analysis

The crystal structure of PC films was characterised by XRD using a SmartLab SE diffractometer (Rigaku, Japan) equipped with Cu-K_α radiation (X-ray tube voltage: 40 kV; current: 40 mA; wavelength: 0.154 nm). The Bragg's angle (2θ) was scanned from 5° to 90° at a scanning rate of 5°/min. The average crystallite size (L) and the interplanar spacing (D) were calculated using Scherrer's and Bragg's equations, respectively, as follows[30]:

$$L = \frac{k\lambda}{\Delta W \cos\theta} \quad (1)$$

$$D = \frac{\lambda}{2\sin\theta} \quad (2)$$

where k is a constant (0.94), λ is the wavelength of the Cu-K_α radiation (0.154 nm), ΔW is the full width at half maxima (FWHM) of the peak, and θ is Bragg's angle. The values of ΔW and θ were obtained by fitting the XRD peaks of the samples using the Lorentz function.

G. Gel permeation chromatography (GPC)

The relative molecular mass and distribution of the PC films were determined by GPC (Agilent 1260 Infinity II) equipped with a differential refraction detector. The chromatography was performed using two Agilent PL gel MIXED-B LS (300 mm×7.5 mm, 10 um) with a mobile phase consisting of dichloromethane at a flow rate of 1 mL/min. The column temperature was set at 30 °C, and the injection volume was 100 uL. Polystyrene was used as the calibration standard. PC film (0.002 g) was completely dissolved in 2 mL dichloromethane and filtered through a 0.45-um filter membrane before sample injection. The molecular weight and distribution of the PC films irradiated at different doses were analysed using Agilent GPC software.

H. Thermal deformation and thermogravimetric analysis

PC films irradiated with different doses were placed in a TLD-2000B far-infrared precision annealing furnace, which was heated (heating rate: 15 °C/min) to 135 °C and held at this temperature for 1 h. The samples were then gradually cooled to 22 °C before being removed for observation of shape changes. Simultaneously, TGA was performed on both irradiated and pristine PC films using NETZSCH TG 209 F3. The temperature was increased from room temperature to 700 °C at a heating rate of 20 °C/min under a nitrogen flow of 60 mL/min. TGA provides quantitative information on the weight change process, allowing assessment of the thermal stability of the samples. The temperature corresponding to the maximum rate of weight loss was recognised as the decomposition temperature of the PC. This study explored the relationship between degradation temperature and absorbed dose.

III. RESULTS AND DISCUSSION

The PC films irradiated with different doses (0–1000 kGy) of EB irradiation are shown in Fig. 1. It can be observed that the PC film without irradiation (0 kGy) is colourless and transparent, whereas the colour of the PC film after irradiation changed by different degrees. With the increase in the absorbed dose, the colour of PC film darkened continuously, from colourless to light yellow to brown yellow. The yellowing of PC after irradiation is a common phenomenon[1]. The high-energy EB is sufficient to break certain chemical bonds in polycarbonate molecules, such as C–H bonds. When these bonds break, the molecular fragments recombine or react with the surrounding material to form chromophores, which absorb specific wavelengths of light to appear yellow. Free radicals are produced in the irradiation process of PC, which re-

acts with hydrogen atoms on the polycarbonate main chain, to deform the polycarbonate main chain, thus changing the colour of polycarbonate. In addition, polycarbonate will undergo oxidation and decomposition reactions under irradiation, and the reaction products will change the configuration of polycarbonate, resulting in colour differences between unirradiated and irradiated samples.

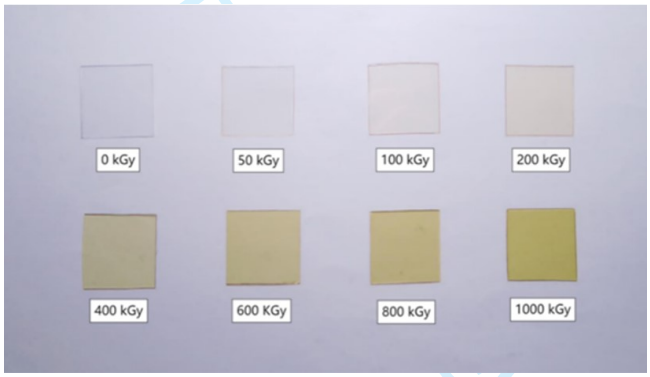

Fig. 1. Appearance of PC films after irradiation treatment with different doses.

A. CIE chromaticity diagram

The CIE chromaticity diagram of pristine and irradiated PC films is shown in Fig. 2-a, and locally enlarged images are presented in Fig. 2-b.

The colours that can be perceived by an average person occupy a region of the chromaticity diagram. The X and Y values are projected coordinates (the chromaticity of the sample is determined by these two parameters). Different colours of the sample appear in different locations of the chromaticity diagram. As can be seen from Fig. 2-b, the colour of PC films moves linearly to the yellow region on the chromaticity diagram as the absorbed dose increases. This makes it possible to detect the absorbed dose by analysing the chroma of PC films. Therefore, the three-dimensional graph of absorbed dose, X value and Y value was established (Fig. 3-a), and the projection of the scatter diagram in Fig. 3-a on the X–Y, X–Z, and Y–Z planes are shown in Fig. 3-b, c, and d, respectively. Their relationship was obtained by fitting. As can be seen from Fig. 3-c and d, the chromaticity value parameters (X and Y values) of PC films increase with the increase of absorbed dose (Z). The X value and Y value showed a two-stage linear relationship with the absorbed dose Z value respectively, with the absorbed dose of 400 kGy as the turning point. When the absorbed dose ranges from 0 to 400 kGy, the chrominance value parameters (X value and Y value) have a linear relationship with the absorbed dose (Z), and when the absorbed dose is 400–1000 kGy, they follow another linear relationship. Moreover, when the absorbed dose is greater than 400 kGy, the X and Y values increase faster with the increase of the dose. Their correlation coefficients ranged from 0.994 to 0.997. Absorbed dose detection within the range of 0–1000

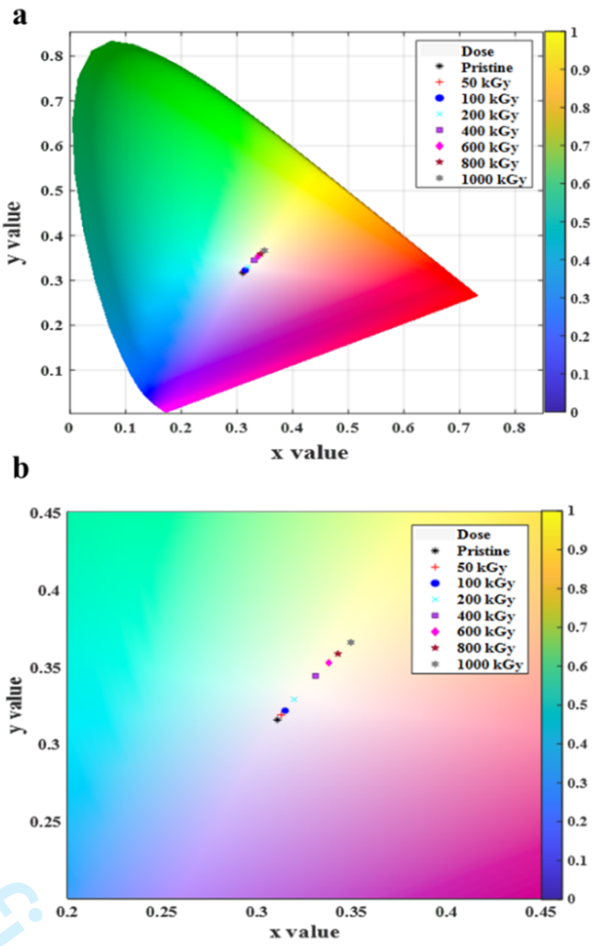

Fig. 2. Distribution of PC film colour in the CIE chromaticity diagram after irradiation treatment with different doses.

kGy (EB) can be realised through chromaticity analysis of irradiated PC films combined with fitting curves in Fig. 3-a, c, and d. Therefore, PC films have the potential for high-dose and extensive-range dose detection. The PC films are readily available and inexpensive, and chrominance measurement is often convenient and quick, making them simpler and cheaper to use as radiochromic dosimeters than other dose-detection methods.

The transmittance of irradiated PC films to visible light of different wavelengths was analysed, and the results are shown in Fig. 3-e. It can be concluded that the light transmittance of the pristine PC film to the whole wavelength range of visible light is approximately 90 %, which is consistent with the production index parameters. The EB irradiation changes the transmittance of PC film to different wavelengths. The transmittance of the irradiated PC films to the wavelength from 700 nm to 400 nm decreases slowly at first and then rapidly as the wavelength decreases. The larger the absorbed dose, the smaller the transmittance of PC films to the same wavelength of light. In addition, when the dose increased from 0 to 400 kGy, the transmittance decreased sharply, and then when the dose continued to increase to 1000 kGy, the light

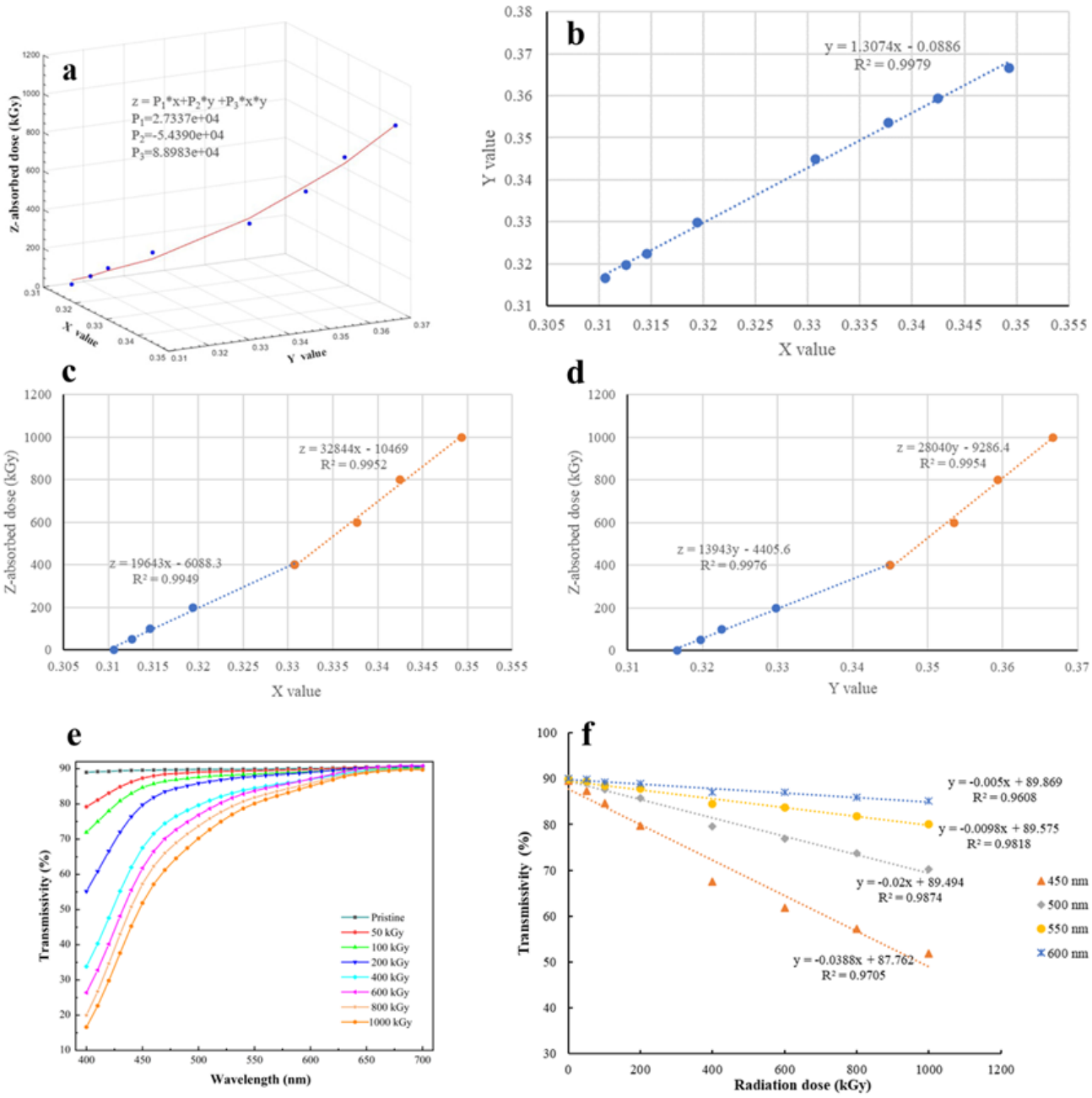

Fig. 3. (a, b, c, d)-Relationship among absorbed dose, X value and Y value; (e)-the transmittance of PC films to visible light after irradiation treatment with different doses; (f)-the relationship between the transmittance of PC films to light of specific wavelengths (450, 500, 550, and 600 nm) and the absorbed dose.

transmittance decreased relatively slowly. The optical transmittance of PC film at 450, 500, 550, and 600 nm varies with the absorbed dose, as shown in Fig. 3-f. It can be seen from the fitting curve that the transmittance of PC films to 500 nm and 550 nm wavelength light has a relatively good linear relationship with the absorbed dose. There is a single linearity between the absorbance value of PC films and the absorbed dose, and the linear correlation coefficient is above 0.98, so the dose measurement can also be achieved by measuring its absorbance value.

B. Fading characteristic analysis

In radiation measurement, the stability of the irradiation signal is an important index. Therefore, the fading characteristics of the chromaticity value of PC films were studied in this study. The changes in chromaticity values (X and Y

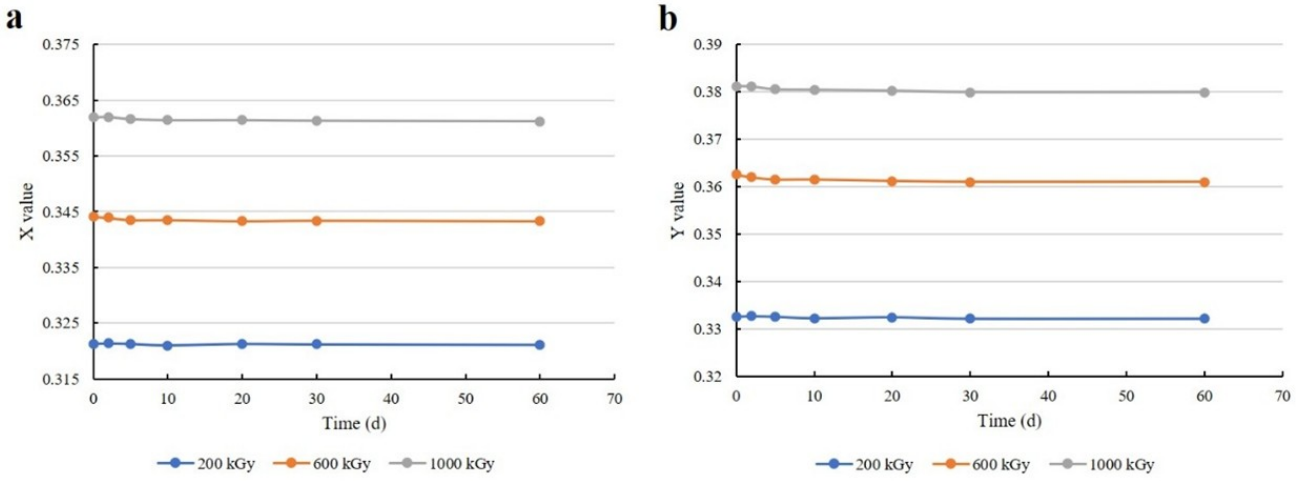

Fig. 4. Change in chromaticity value (X and Y values) of irradiated PC films with time

values) of PC films irradiated with different doses (200, 600, and 1000 kGy) within 60 days are shown in Fig. 4-a, b. It can be seen that both the X value and the Y value only decrease slightly (the decline was no more than 0.3 %) in the first 5 days and then remain stable. Therefore, the nuclear signal (chromatic value) formed by radiation is stable in the PC film. The decline in colour is related to environmental factors such as light, UV, temperature, humidity, and oxygen content. Therefore, as long as the irradiated PC films are stored in a suitable environment, the stability of the radiation signal stored in the film can be maintained. Compared with the photoluminescence signal of PC (which has a large degree of attenuation in the short term), the long-term stability of the chromatic value signal is a major advantage.

C. UV–visible spectrum

The original absorption spectra of irradiated and unirradiated PC films were measured by a UV–visible light absorption spectrometer. The unirradiated PC films was selected as the blank control group. The net absorbance was obtained by subtracting the absorption spectrum of the unirradiated PC film from the original absorption spectrum of the irradiated PC film, as shown in Fig. 5-a. It can be seen that the irradiated PC film has a strong absorption peak at 290–500 nm. The greater the absorbed dose, the greater the absorbance value of PC film. At the same time, the relationship between the absorbance of PC film for a specific wavelength in the range of 340–450 nm and absorbed dose is shown in Fig. 5-b. It can be seen that there is a relatively good linear relationship between the net absorbance of PC films at 350, 370, 390, 410, 430, and 450 nm and the absorbed dose (linear correlation coefficient greater than 0.995).

D. XRD spectrum

The XRD patterns of PC films irradiated with different doses in the range of 0–600 kGy are shown in Fig. 6. It is evident from the figure that the primary peak is in the range of 12°–30°. The wide diffraction peak indicates that the crystal size of the PC film is small, and it is a partially crystalline polymer dominated by an amorphous phase[4]. In addition, with the increase in absorbed dose, the intensity of the diffraction peak decreases, indicating that the crystallinity of PC decreases. It is possible that free radicals form in the PC crystal region due to irradiation, which reacts with the crystal fragments and destroys the crystal structure.

Table 1. Calculated values of crystallite size (L) and interplanar spacing (D).

Dose (kGy)	2θ (degree)	ΔW (radians)	L (nm)	D (nm)
0	17.04	0.1137	1.29	0.519
50	16.96	0.1164	1.26	0.522
100	16.94	0.1198	1.23	0.523
200	16.96	0.1201	1.21	0.522
400	17.22	0.1248	1.17	0.515
600	17.00	0.1273	1.15	0.521

Table. 1 specifies the crystal size (L) and interplanar spacing (D) of PC after different doses of irradiation. Their values change with the dose of the EB irradiation. When the absorbed dose increases from 0 kGy to 600 kGy, the crystal size (L) decreases from 1.29 nm to 1.15 nm. Polymers usually undergo cross-linking and degradation reactions under irradiation. These reactions cause local order changes within the polymer, which can be reflected in changes in the crystal structure. EB irradiation causes a local temperature increase in the material, and this thermal effect can cause the atoms inside the material to rearrange and introduce various types of defects in the material, such as vacancies, interstitial atoms, and dislocations. These defects can affect the growth and sta-

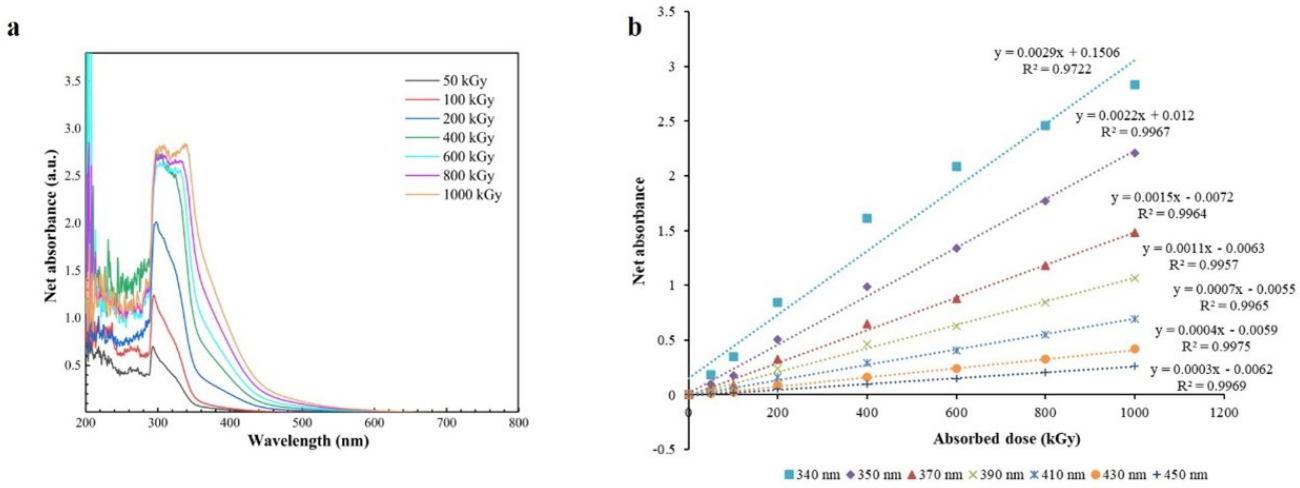

Fig. 5. (a)-Net absorbance of PC films treated with different doses (50–1000 kGy) of irradiation; (b)-the relationship between the net absorbance of PC films at specific wavelengths (340–450 nm) and the absorbed dose.

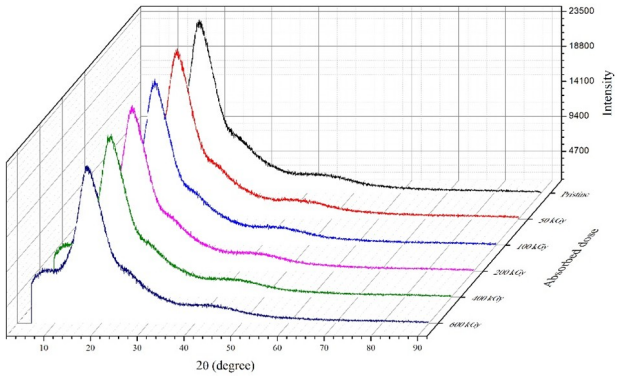

Fig. 6. XRD patterns of PC films irradiated with different doses.

bility of the crystal. Furthermore, electron beam irradiation may trigger oxidation or reduction reactions on the surface of the material, which may change the surface energy of the material, thus affecting the size and morphology of the crystal.

E. Molecular weight analysis

The GPC technique was employed to determine the molecular weight of PC. Fig. 7 displays the molecular weight distribution of polycarbonate after different doses of irradiation. It can be concluded that the molecular weight of PC film is mainly distributed between 1×10^3 g/mol and 2×10^5 g/mol. With the increase in absorbed dose, the molecular weight distribution curve and cumulative integral curve have a tendency to shift to the left, and the proportion of high molecular weight region decreases, while the proportion of low molecular weight region increases. This indicates that the degradation of PC under electron beam irradiation is dominant, resulting in an overall reduction in molecular weight. Meanwhile, peak average molecular weight (M_p, g/mol), number average molecular weight (M_n, g/mol), and weight average molecular weight (M_w, g/mol) were analysed. The obtained results are encapsulated in Table. 2.

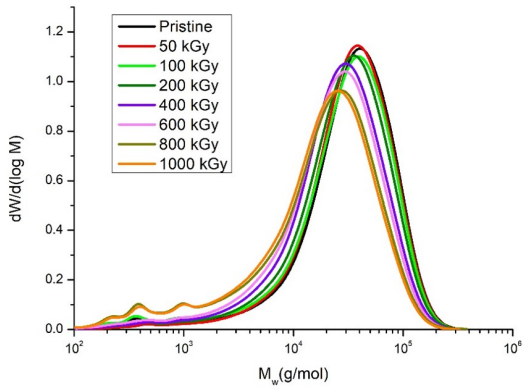

Fig. 7. The molecular weight distribution and cumulative integral curve of PC.

M_p indicates that the molecular weight is mainly distributed around here; M_n reflects the characteristics of small molecules of materials; M_w reflects the properties of macromolecules in the material. Macromolecules can better reflect the characteristics of polymer materials, so the change in M_w was discussed in this study. M_p generally decreased with the increase in irradiation dose. When the absorbed dose gradually increases to 1000 kGy, Mw decreased from 44585 g/mol to 27494 g/mol. Eq.(3) was used to calculate the degree of polymerization of PC after different doses of irradiation. The results showed that the polymerization degree of PC decreased from 176 to 108. This indicates that PC is a degraded

polymer under electron beam irradiation of less than 1000 kGy. The main reason for the degradation of polycarbonate under electron beam irradiation is the main chain break caused by electron beam energy and the oxidation degradation accelerated by free radicals generated during irradiation

$$n = \frac{M_w}{M} \tag{3}$$

(M-Molecular weight of PC monomer, 254; n-Degree of polymerization)

Table 2. Molecular weight statistical results.

Dose (kGy)	M_p (g/mol)	M_n (g/mol)	M_w (g/mol)	n
0	40218	8264	44585	176
50	38295	12453	43871	173
100	39053	7064	42057	166
200	35408	9457	39872	157
400	29976	8199	35183	139
600	29394	6878	32658	129
800	27178	3772	29193	115
1000	25129	3844	27494	108

F. Thermal deformation and Thermogravimetric analysis

The thickness of the material in this study did not fulfill the requirements of thermomechanical analysis (TMA). Therefore, quantitative thermal deformation analysis was not carried out, only qualitative analysis was performed. The deformation degree of PC films heated at 130 °C for 1 h is shown in Fig. 8-a. It can be seen that the pristine sample without irradiation did not deform, while the sample irradiated with 1000 kGy was completely bent. The bending degree of PC increased with the increase of absorbed dose from 0 to 1000 kGy. This is related to the degradation of PC under irradiation. From the above research results, it can be seen that the molecular weight of PC decreases under irradiation, which leads to a decrease in its thermal deformation resistance. In the follow-up study, the thermal deformation temperature of PC films treated with different doses of radiation can be further studied by the thermomechanical analysis method (the material is placed in a specific heating environment and a certain load is applied. As the temperature rises, the material will deform, and when the deformation reaches a preset value, the temperature at this time is the thermal deformation temperature).

As can be seen in Fig. 8-b, PC film shows degradation in two stages. The first stage occurs in the temperature range of 420–558 °C, and the PC mass is lost by about 66 %. The second stage occurs in the temperature range of 558–700 °C, and the PC mass is reduced by 20.2 %. Therefore, the temperature range of main degradation was determined to be 420–558 °C. Compared to the first stage, PC quality decreases more slowly in the second stage. Jang et al. (2004) concluded that the evolution of H_2O and CO_2 accompanies the entire thermal decomposition process of PC[31]. In the first stage, alcohols, ethers, and carbonates are mainly detected. In the second stage, carbonate was rearranged to form a cross-linked structure and finally carbonized. In this study, the temperature (T_m) corresponding to the peak point of the DTG curve was used to analyse the thermal stability of the PC film sample. A larger T_m means that the sample is more heat-resistant. Fig. 8-c displays the temperature (T_m) corresponding to PC films irradiated at different doses. When PC film was irradiated by 50 kGy electron beam, T_m increases from 517.2 to 531.2 °C compared with unirradiated PC film. This may be due to the enhancement of thermal stability of PC films by irradiation polymerization at lower doses. However, when the dose was increased to 100 kGy, the irradiation degradation process of PC was gradually enhanced, resulting in a decrease in T_m. This result is consistent with the result reported by Jaleh et al. (2007)[7]. With the further increase in

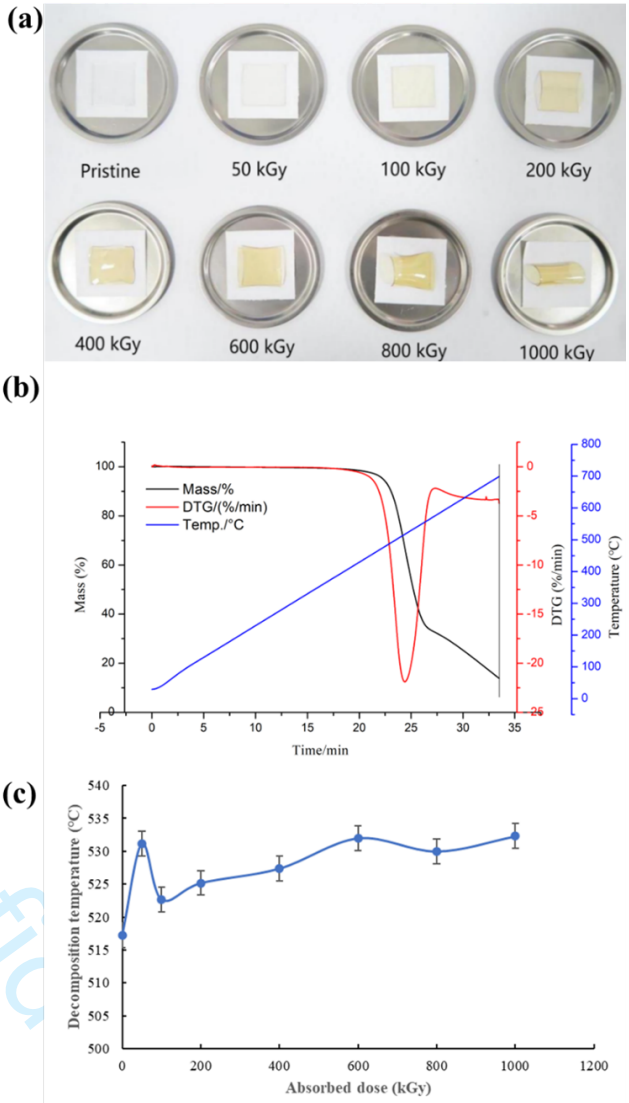

Fig. 8. (a)-Appearance of irradiated PC films (0–1000 kGy) after heat treatment at 130 °C for 1 h; (b)-thermogravimetric analysis curve of PC film; (c)-the relationship between PC decomposition temperature and absorbed dose.

the absorbed dose, the irradiation degradation process began to dominate, and the heat-resistant molecular structure was generated during the irradiation degradation process, which enhanced the thermal stability of PC. Irradiation may introduce new functional groups or change the properties of existing functional groups, improve the antioxidant properties of polycarbonate, thus slowing down its degradation rate at high temperatures, and change the intermediate products and final products produced during the thermal degradation of PC, thereby affecting its thermal degradation behaviour.

IV. CONCLUSION

In this study, the optical and structural properties of PC films after EB irradiation were investigated. It can be concluded that the chroma value and absorbance value of PC film have a good relationship with the absorbed dose. Therefore, the detection of absorbed dose can be realized through the measurement of chroma value or absorbance. The radiation signal (chroma value) stored inside the PC remains essentially unchanged for 60 days. At the same time, the main chain of PC was broken and its molecular structure changed under irradiation. The crystallinity, crystal size, weight average molecular weight, and polymerization degree decrease with the increase of dose. However, the thermal stability of irradiated PC is higher than that of unirradiated PC. Other dosimetry properties of PC radiochromic film dosimeters, such as repeatability, intra-batch uniformity, dose rate dependence, annealing characteristics, and the effects of temperature and humidity on radiation detection stability and radiation signal storage, can be further developed in subsequent studies.

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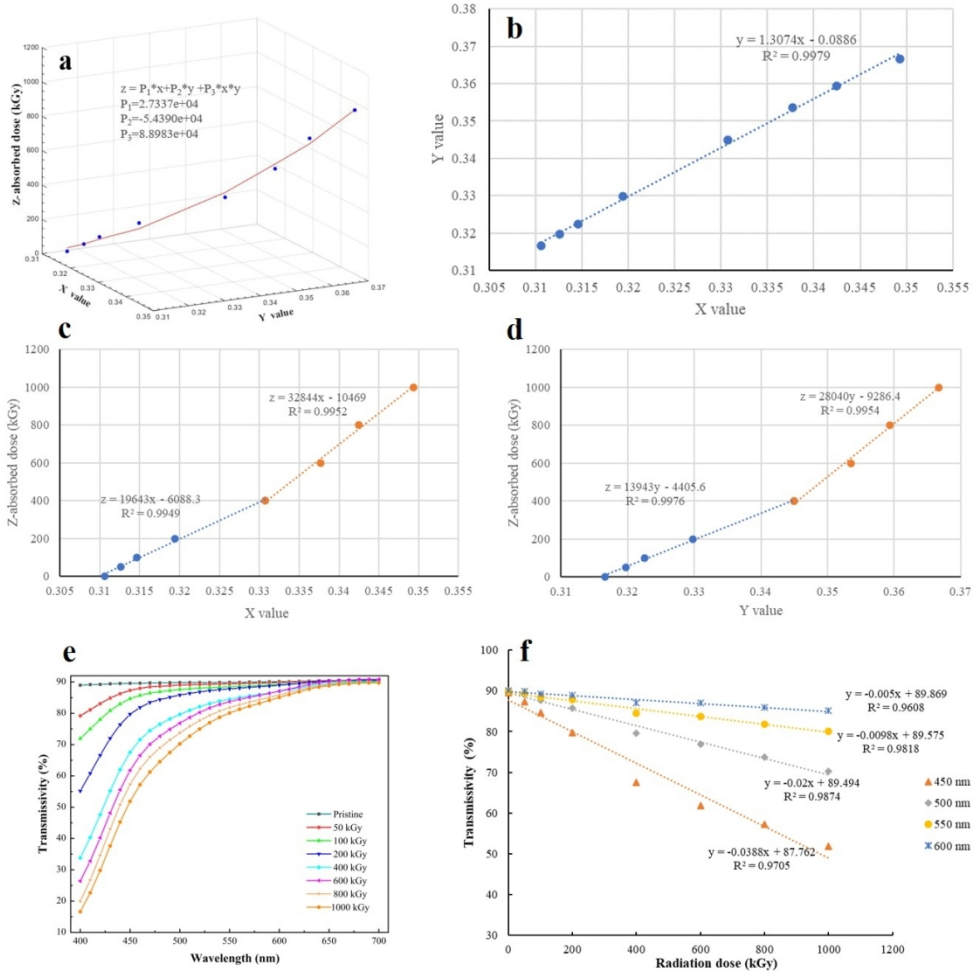

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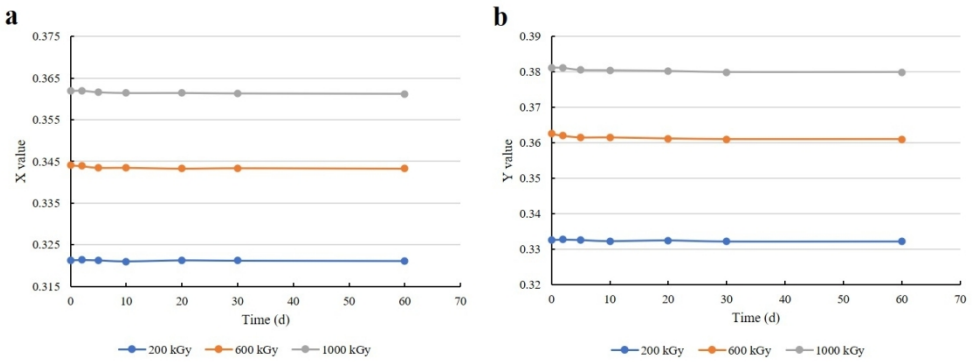

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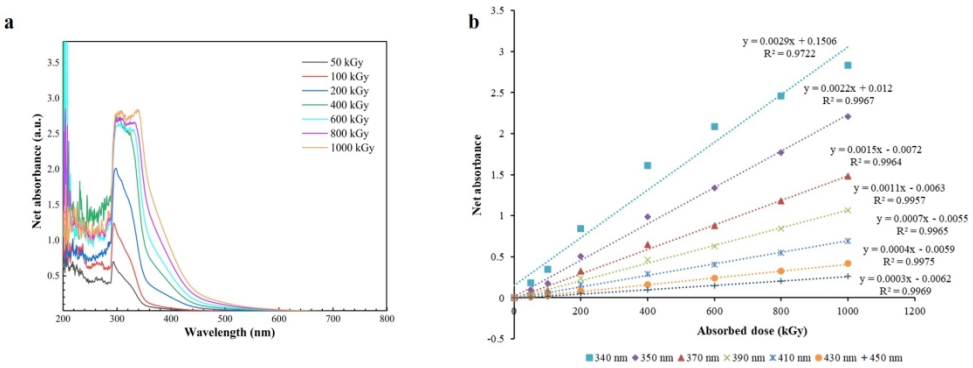

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