

Effective compatibilization of poly(L-lactic acid)/poly(butylene adipate-co-terephthalate) blends via low-dose gamma irradiation

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ABSTRACT

This study addresses the critical challenge of compatibilizing immiscible poly(lactic acid) (PLA) and poly(butylene adipate-co-terephthalate) (PBAT) blends. The aim is to investigate low-dose gamma irradiation (3–5 kGy) as an efficient and clean method to enhance the interfacial adhesion and overall performance of these biodegradable polymer blends, overcoming the limitations of conventional compatibilization techniques. PLA pellets were subjected to gamma irradiation at 3 and 5 kGy before being melt-blended with PBAT in a 50/50 wt% ratio using a twin-screw extruder. The resulting blends were comprehensively characterized to evaluate their molecular, mechanical, morphological, thermal, and rheological properties. Low-dose gamma irradiation induced controlled chain scission in PLA, reducing its molecular weight. This modification significantly improved the compatibility of PLA/PBAT blends, leading to a more homogeneous morphology with elongated PBAT domains. Consequently, the mechanical properties were enhanced, with the 3 kGy irradiated blend showing a 7.7% increase in yield stress and an 8.6% increase in elongation at break compared to the non-irradiated blend. Furthermore, the thermal stability of the blend irradiated at 3 kGy improved, with the onset degradation temperature increasing by 5.3 °C. Low-dose gamma irradiation is a highly effective and promising strategy for compatibilizing PLA/PBAT blends. The controlled degradation of PLA enhances interfacial adhesion, leading to a synergistic improvement in mechanical and thermal properties without the drawbacks of high-dose irradiation or chemical additives. This method offers a scalable and environmentally friendly pathway to develop high-performance, fully biodegradable materials for sustainable packaging and other advanced applications.

1. Introduction

The escalating global plastic pollution crisis poses an unprecedented threat to ecosystems and human health, demanding urgent and innovative solutions [1]. In 2023, global plastic production reached an alarming 436 million metric tons, with projections indicating a near doubling to 884 million metric tons by 2050 [2,3]. A significant portion of this production contributes to environmental contamination, with estimates suggesting that between 1 and 2 million tons of plastic waste leak into aquatic ecosystems annually, exacerbating climate change, ocean acidification, and biodiversity loss [4]. This dire situation and escalating issue of microplastics has catalyzed intensive research into sustainable alternatives, particularly biodegradable polymers, which offer a promising pathway to mitigate the environmental footprint of conventional plastics [5].

Among the leading candidates for sustainable polymeric materials are poly(lactic acid) (PLA) and poly(butylene adipate-co-terephthalate) (PBAT) [6]. PLA, a bio-based polyester derived from renewable resources such as corn starch or sugarcane, is highly attractive due to its biodegradability, compostability, biocompatibility, and excellent mechanical properties, including high stiffness and tensile strength (typically 21–60 MPa) [7,8]. Its transparency and processability make it suitable for various applications, from packaging to biomedical devices [9]. Lactic acid is chiral because its central carbon atom is bonded to four different groups, resulting in two enantiomeric forms: L- and D-lactic acid. Chemically synthesized lactic acid yields a racemic mixture (50% D, 50% L), whereas fermentation typically produces >99% L-isomer. Poly(L-lactic acid) (PLLA), derived from L-lactide, shows greater crystallinity and chemical stability than poly(D-lactic acid) (PDLA), which is made from D-lactide [10,11]. However, PLA suffers from

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inherent limitations, primarily its brittleness, low elongation at break (often below 10%), poor impact resistance, which restrict its use in applications requiring flexibility and toughness, and a slow degradation rate influenced by factors such as crystallinity, molecular weight and its distribution, morphology, water diffusion rate, and stereoisomeric content [12].

To overcome PLA's shortcomings, blending it with more ductile polymers has emerged as a viable strategy. Poly(butylene adipate-co-terephthalate) (PBAT), a petroleum-based but fully biodegradable aliphatic-aromatic copolyester, is an ideal complement to PLA [13]. PBAT is renowned for its exceptional flexibility, high elongation at break (exceeding 1000%), and toughness, making it suitable for flexible packaging and agricultural films [14,15]. Blending PLA with PBAT can synergistically combine PLA's stiffness and biodegradability with PBAT's ductility and toughness, yielding materials with a balanced property profile [16]. Despite their complementary attributes, PLA and PBAT are largely immiscible due to significant differences in their chemical structures and melting viscosity [17]. This immiscibility leads to phase separation, poor interfacial adhesion, and consequently, inferior mechanical properties in their blends, often manifesting as a reduction in tensile strength and elongation at break compared to the individual components [17,18]. Therefore, effective compatibilization strategies are crucial to enhance interfacial interactions, promote homogeneous morphology, and unlock the full potential of PLA/PBAT blends.

According to miscibility, polymer blends can be classified into three categories: miscible blends, compatible blends, and immiscible blends [19]. Miscible blends form a single-phase system with a homogeneous morphology and exhibit a single glass transition temperature (T_g) intermediate between those of the pure components, reflecting a negative free energy of mixing, and their formation depends on factors such as chemical structure, polarity, viscosity ratio, interfacial tension, and specific interactions like hydrogen bonding, dipole-dipole forces, acid-base interactions, and dispersive forces [20]. Compatible blends display a fine-phase morphology with improved properties; in these systems, one component is partially dissolved in the other, resulting in two distinct but shifted T_g values, each moving toward the T_g of the other component, indicating limited mutual solubility [19]. In contrast, most polymer blends are immiscible due to the negligible entropy gain upon mixing high-molecular-weight polymers; they exhibit two separate T_g and melting temperatures (T_m), corresponding to each phase, along with a sharp interphase that reflects weak intermolecular interactions, typically limited to van der Waals forces or occasional hydrogen bonding, and a lack of strong thermodynamic compatibility [21].

Therefore, to improve compatibility, various compatibilization methods have been explored to address the immiscibility of PLA/PBAT blends, including the use of reactive compatibilizers (e.g., maleic anhydride-grafted polymers), block copolymers, and the incorporation of nanoparticles [22–24]. While these methods have shown promise in improving blend properties, they can involve complex synthesis routes, additional chemical additives, or intricate processing steps, which can increase production costs and potentially introduce new environmental concerns [25,26]. This necessitates the exploration of alternative, more efficient, and environmentally benign compatibilization techniques.

Radiation-induced modification, particularly gamma irradiation, offers a non-toxic compelling alternative for enhancing polymer compatibility by inducing controlled chemical changes within the polymer matrix [27]. Gamma irradiation can lead to chain scission, crosslinking, and degradation, depending on factors such as polymer's structure, irradiation dose, concentration of additives, and conditions of irradiation (e.g., atmosphere and temperature) [28]. Radiation processing can change a polymer's molecular weight, hydrophilicity, and mechanical properties through radiolysis, which refers to the dissociation of molecules by nuclear radiation [29,30]. The last few years have seen a significant surge in research focusing on the radiation-induced modification of polymers, particularly using gamma irradiation, to address challenges in materials science and sustainability [31,32].

Recent reviews underscore that gamma irradiation remains a powerful tool for structural modification, enabling controlled crosslinking, chain scission, and grafting to tailor polymer properties [31]. For instance, Elsayw et al. [33] exposed PLA and a 3% chitosan nanoparticle nanocomposite to 5–40 kGy γ -irradiation (^{60}Co , ambient conditions) to see how γ -irradiation affected their characteristics. Increasing gamma irradiation dose reduced molecular weight of PLA (indicating oxidative degradation and chain scission) and decreased tensile strength, elongation at break, melting temperature (T_m), and glass transition temperature (T_g). Crystallization peak temperatures dropped for PLA irradiated in solution, and thermal stability declined with dose, especially in chloroform-irradiated samples. However, in Rashed Almasri's study [34], PLA reinforced with microcrystalline cellulose (MCC) was γ -irradiated at 10, 30, and 50 kGy in vacuum and air. Vacuum irradiation promoted crosslinking, increasing tensile strength, thermal stability, and crystallinity (evidenced by the disappearance of the glass transition temperature above 10 kGy) though this may slightly hinder processability. In contrast, irradiation in air induced oxidative degradation and chain scission, reducing tensile strength, elongation at break, and crystallization temperature, consistent with mechanical degradation.

For compatibilization purposes, this high-energy irradiation can induce chain scission, creating bond cleavages and free radicals that promote molecular reactions, improve interfacial adhesion, and enable grafting between immiscible polymer phases [35]. Previous studies have investigated the effects of gamma irradiation on PLA to produce PLA/PBAT blends, focusing on high irradiation doses (e.g., 80–150 kGy) [36,37]. While high doses can induce significant structural alterations and improve certain properties, they frequently result in excessive polymer degradation, leading to embrittlement and substantial reduction in overall mechanical performance [38]. For instance, PLA's tensile properties remain stable up to approximately 20 kGy and doses above 30 kGy have been shown to cause significant decay in PLA mechanical properties [39]. Zhou et al. [40] γ -irradiated poly(lactide)/poly(butylene adipate-co-terephthalate)/carbon nanotubes (PLA/PBAT/CNTs) composites at 6, 12, and 24 kGy to tune microstructure and enhance interfacial interactions. Mechanical properties of the blends improved significantly after irradiation, with the greatest gains at 6 kGy (tensile strength rose from 31.9 to 42.1 MPa and elongation at break from 160% to 230%). At higher doses, tensile strength plateaued while elongation decreased, likely due to competing chain scission within the crosslinked network. This recent body of work emphasizes a critical research gap: the need to explore lower irradiation doses that can induce beneficial chemical modifications and enhance compatibilization without compromising the material's structural integrity and mechanical properties.

Fig. 1 schematically illustrates radiation-induced modifications within and between phases of polymer blends, using PLA (polymer A) and PBAT (polymer B) as an example. Melt extrusion or even solution blending of irradiated and immiscible polymers can trigger crosslinking or chain scission, effects governed by polymer type and irradiation dose (which higher doses favor chain scission). Controlled gamma irradiation is crucial to improve interfacial compatibility in immiscible blends and promote crosslinking, which occurs predominantly in the amorphous phase due to its disordered, mobile chains that facilitate radical formation and recombination into a 3D network. However, excessive scission can lead to degradation and compromised mechanical performance [41].

This article addresses this gap by focusing on the compatibilization of PLA/PBAT blends through the application of low-dose gamma irradiation to PLA prior to blending with PBAT, evaluating doses of 0, 3, and 5 kGy, selected based on preliminary studies indicating optimal outcomes up to 6 kGy [40]. The objective of this study is to investigate whether these lower doses can effectively promote interfacial adhesion and significantly improve the mechanical, thermal, and morphological properties of PLA/PBAT blends, thereby offering a more sustainable and

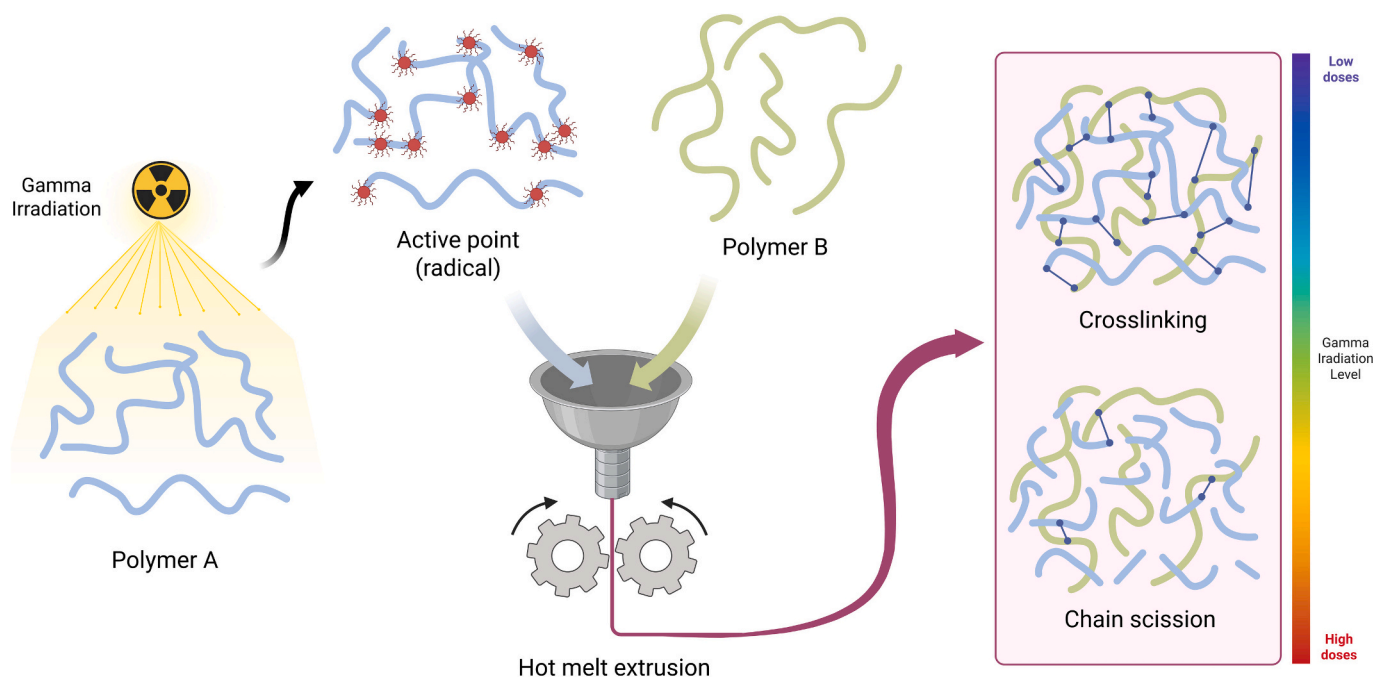


Fig. 1. Mechanism diagram of radiation-induced modification in polymer blends.

efficient compatibilization strategy. Specifically, we hypothesize that controlled low-dose irradiation will generate limited but sufficient concentration of free radicals in PLA, primarily within its amorphous regions, without triggering extensive chain scission or oxidative degradation. During subsequent melt blending with PBAT, these radicals are expected to promote reactive compatibilization at the polymer–polymer interface, favoring crosslinking reactions over degradation (as schematically illustrated in Fig. 1). The study aims to provide detailed insights into the effects of low-dose irradiation on the blend's properties, contributing to the development of advanced biodegradable materials for diverse applications, particularly in sustainable packaging.

2. Materials and methods

2.1. Materials

Ingeo™ Biopolymer 3D850 pellets, provided by NatureWorks LLC (Minnetonka, MN, USA), is a semi-crystalline poly(lactic acid) (PLA) composed primarily of poly(L-lactide) (PLLA) with only 0.5% D-isomer and 0.15% residual lactide (per the manufacturer's certificate). This semi-crystalline grade is tailored for fused filament fabrication (FFF) 3D printing due to its enhanced heat resistance [42]. Poly(butylene adipate-co-terephthalate) (PBAT) pellets (Ecoflex® F Blend C1200) were provided by BASF SE (Florham Park, NJ, USA). Antioxidant (Irganox® 1010) was acquired from Easy Química LTDA (Mogi das Cruzes, SP, Brazil). All materials were used as received without further purification.

2.2. Gamma irradiation of PLA

PLA pellets were subjected to gamma irradiation at the Radiation Technology Center (CETER) of IPEN-CNEN/SP, Brazil. A Cobalt-60 source was used to deliver low doses of 3 kGy and 5 kGy at an average rate of $2.7 \text{ kGy} \cdot \text{h}^{-1}$. The irradiation was performed in an air atmosphere at a controlled room temperature of $25 \pm 1^\circ\text{C}$. After irradiation, PLA pellets were stored at room temperature ($25 \pm 1^\circ\text{C}$) for approximately one month before further processing.

2.3. Preparation of PLA/PBAT blends

PLA/PBAT blends were prepared with a 50/50 wt%/wt% composition. Both non-irradiated PLA and irradiated PLA (at 3 kGy and 5 kGy) were blended with PBAT. An antioxidant, Irganox 1010, was incorporated into the blends at 0.3 wt%. Compounding was performed using a Thermo Fisher Scientific Haake Rheomex 332p co-rotating twin-screw extruder with a 16 mm screw diameter and an L/D ratio of 25. All samples were manually mixed and added together into the extruder feed hopper. The extrusion conditions included a temperature of 145°C across six zones, a screw speed of 80 rpm, and a 4% feed rate. The residence time in the extruder was approximately 5 to 6 min. After extrusion, the material was cooled to room temperature and granulated into pellets with 1.0 mm using a VariCut pelletizer type 567-5030 from Thermo Fisher Scientific Inc.

Afterwards, the test specimens were produced using injection molding using a Babyplast 10/12 Standard horizontal injection machine. The process parameters were set as follows: an injection speed of 90%, an actual injection pressure of 360 bar, and a post-injection pressure of 310 bar. The injection time was 1.5 s, with a post-injection time of 8 s and a cooling time of 13 s. The plasticization temperature was set to 170°C , the nozzle temperature to 174°C , and the nozzle tip temperature to 180°C . Additionally, the decompression distance was 8 mm, performed at 70% speed, and the material's residence time in the heated section ranged from 1 to 2 min. A steel mold compliant with ASTM D638–14 [43] for type IV specimens was used to prepare dog-bone shaped specimens.

2.4. Characterization techniques

2.4.1. Gel permeation chromatography (GPC)

Gel permeation chromatography was used to evaluate the molar mass distribution (MMD), polydispersity index (D), and molecular weight averages (M_n , M_w , M_z , and M_p) of PLA and PBAT pellets. The analysis was performed using a Waters instrument, equipped with a 1525 binary HPLC pump and a 2414 refractive index detector. The mobile phase consisted of tetrahydrofuran (THF), filtered through a $0.45 \mu\text{m}$ membrane, and delivered by a Waters 1525 pump system. Two $7.8 \times 300 \text{ mm}$ columns with $5 \mu\text{m}$ particles (KF-800 Shodex) were

maintained at 40 °C, while the refractive index detector (Waters 2414) was set to 20 °C. The prepolymer sample, prepared at a concentration of 3.00 mg.mL⁻¹, was manually injected and passed through the system at a flow rate of 1.00 mL.min⁻¹. Equipment calibration was performed using monodisperse polystyrene standards with molar masses of 1.8 × 10⁴, 3.8 × 10⁴, 9.6 × 10⁴, 1.9 × 10⁵, 3.5 × 10⁵, and 7.1 × 10⁵ g.mol⁻¹, under the same concentration and flow conditions as the samples.

2.4.2. Tensile mechanical properties

Tensile tests were conducted according to ASTM D638-14 [43] using an Instron-EMIC universal testing model DL 3000 machine. The tests were performed at a crosshead speed of 5 mm/min, a 20 kN load cell, and controlled environmental conditions of 25 ± 5 °C and 50% ± 5% relative humidity. At least five specimens were tested for each formulation. Yield stress, yield strain, tensile strength (stress at break), elongation at break, and tensile modulus were determined.

2.4.3. Scanning Electron Microscopy (SEM)

The morphology of the fractured surfaces of the PLA/PBAT blends was examined using a JSM-IT700HR Scanning Electron Microscope equipped with a FEG Schottky electron gun and with accelerating voltage of 5.0 kV. Specimens were cryogenically fractured after immersion in liquid nitrogen. The fractured surfaces were then sputter-coated with a thin layer of gold/palladium. Fracture images of the blends were obtained at the magnitude of x5.0 k.

2.4.4. Attenuated Total Reflection – Fourier Transformed Infrared Spectroscopy (ATR-FTIR)

FTIR spectra were recorded using a Perkin Elmer Spectrum 100 (USA) equipment coupled to the ATR Pike model MIRacle (USA) apparatus. Spectra were collected in the range of 4000 to 500 cm⁻¹ with a resolution of 4 cm⁻¹ and 16 accumulations.

2.4.5. X-ray diffraction (XRD)

X-ray diffraction analysis was performed using a Bruker D2 Phaser diffractometer with CuKα radiation (λ = 1.54184 Å). Data were collected with a continuous scan of 2θ/θ between 5 and 60° 2θ, with an energy of 30 kV, 10 mA and sweep speed of 0.05°/s. The degree of crystallinity (X_{CXRD}) was determined by calculating the ratio of the crystalline area to the total area, as shown in Eq. (1).

$$X_{CXRD} = \frac{A_c}{A_a + A_c} \times 100 \quad (1)$$

where A_c represents the area corresponding to the crystalline phase, and A_a denotes the area associated with the amorphous phase. All calculations were carried out using the Fityk software and the amorphous halo was deconvoluted using a Gaussian function, while the crystalline peaks were analyzed using a Voigt function.

2.4.6. Rheological properties

The rheological behavior of PLA, PBAT, and their blends was investigated using a MCR302 rheometer (Anton-Paar), equipped with parallel plates (25 mm diameter). The samples were positioned between the parallel plates and melted at a temperature of 170 °C. The pellets were evenly distributed to fully cover the plate's surface. Once the temperature reached 170 °C, the gap between the plates was adjusted to 1 mm, allowing excess material to be removed and ensuring proper sample preparation for testing. To evaluate the viscoelastic properties, dynamic frequency sweep tests were performed. Initially, a linear viscoelasticity range (LVR) test was conducted at 170 °C, applying a strain range of 0.1% to 10%, to determine the optimal amplitude for the frequency sweep. The limit of the linear viscoelastic regime was identified at 1% strain. The frequency sweep tests were carried out over an angular frequency range of 150–0.1 rad/s (on a logarithmic scale), with 30 measurement points recorded. Measurements of complex viscosity

(η*), storage modulus (G'), and loss modulus (G'') were conducted in the molten state.

2.4.7. Differential scanning calorimetry (DSC)

Differential scanning calorimetry was performed using a TA Instruments DSC 25 (USA) equipment coupled with a refrigerated cooling system (RCS) according to ASTM D3418-12 [44]. The analysis was performed under nitrogen flow of 50 mL/min and involved three distinct stages. First, the samples were heated at a rate of 10 °C/min to 170 °C. They were then cooled back down to -30 °C at the same rate to eliminate any previous thermal history. After maintaining the samples at -30 °C for 5 min, they were reheated to 170 °C at a rate of 10 °C/min. This process enabled the determination of key thermal properties, including the glass transition temperature (T_g), cold crystallization temperature (T_{cc}), cold crystallization enthalpy (ΔH_{cc}), melting temperature (T_m), melting enthalpy (ΔH_m), hot crystallization temperature (T_{hc}), and hot crystallization enthalpy (ΔH_{hc}) for each sample. The degree of crystallinity (X_{cDSC}) was determined using Eq. (2), which incorporates the melting enthalpy (ΔH_m), the cold crystallization enthalpy (ΔH_{cc}), the melting enthalpy of a 100% crystalline material (ΔH_m⁰, assumed to be 114 J/g for PBAT and 93 J/g for PLA) [37], and the mass fraction (w) of PLA or PBAT in the blend.

$$X_{cDSC} = \frac{\Delta H_m - \Delta H_{cc}}{\Delta H_m^0} \times \frac{100}{w} \quad (2)$$

2.4.8. Thermogravimetric analysis (TGA)

Thermogravimetric analysis was conducted on a Mettler Toledo TGA/DSC 3+ STARE System (Mettler Toledo, Greifensee, Switzerland) to evaluate the thermal degradation behavior of the materials according to ASTM E1131-20 [45]. Samples were heated from 30 °C to 600 °C at a rate of 10 °C/min under a nitrogen atmosphere at a rate of 50 mL/min. For each experiment, a sample weighing 10 ± 3 mg was placed into a 70 μL alumina crucible without lid. Onset degradation temperature (T_{onset}), temperature at the maximum rate of degradation (peak in the DTG curve, TD_{TC}) temperature at 5% weight loss (T_{5%}), temperature at 50% weight loss (T_{50%}), and residual mass at 600 °C (R_{600 °C}) were determined.

2.4.9. Dynamic mechanical analysis (DMA)

Dynamic mechanical analysis was performed on rectangular specimens of PLA, PLA irradiated, PBAT, and their blends, with dimensions of 6 × 30 × 1 mm. The tests were conducted using a DMA Q800 dynamic mechanical analyzer from TA Instruments. The equipment operated in uniaxial tension mode, with a temperature range of -60 to 80 °C and a heating rate of 3 °C/min under air atmosphere. The samples were analyzed at a fixed frequency of 1 Hz, an amplitude of 10 μm, and a preload force of 0.15 N.

3. Results and discussion

3.1. Molecular weight measurements

The effect of gamma irradiation on the molecular weight distribution (MWD) and molecular weight fractions of PLA was investigated using gel permeation chromatography (GPC). The MWD profiles for both untreated and irradiated samples are depicted in Fig. 2, with the corresponding molecular weight fraction data (M_n, M_w, M_z, M_p) presented in Table 1. For PLA exposed to 3 kGy of gamma irradiation, a noticeable decrease in molecular weight was observed, attributed to chain scission caused by the irradiation process [46]. This reduction is reflected across all molecular weight fractions (M_n, M_w, M_z, M_p), indicating the breakdown of polymer chains into smaller fragments.

At 5 kGy, however, the decline in molecular weight becomes less significant, and a partial recovery in the molecular weight fractions is evident. This suggests that secondary mechanisms, such as chain

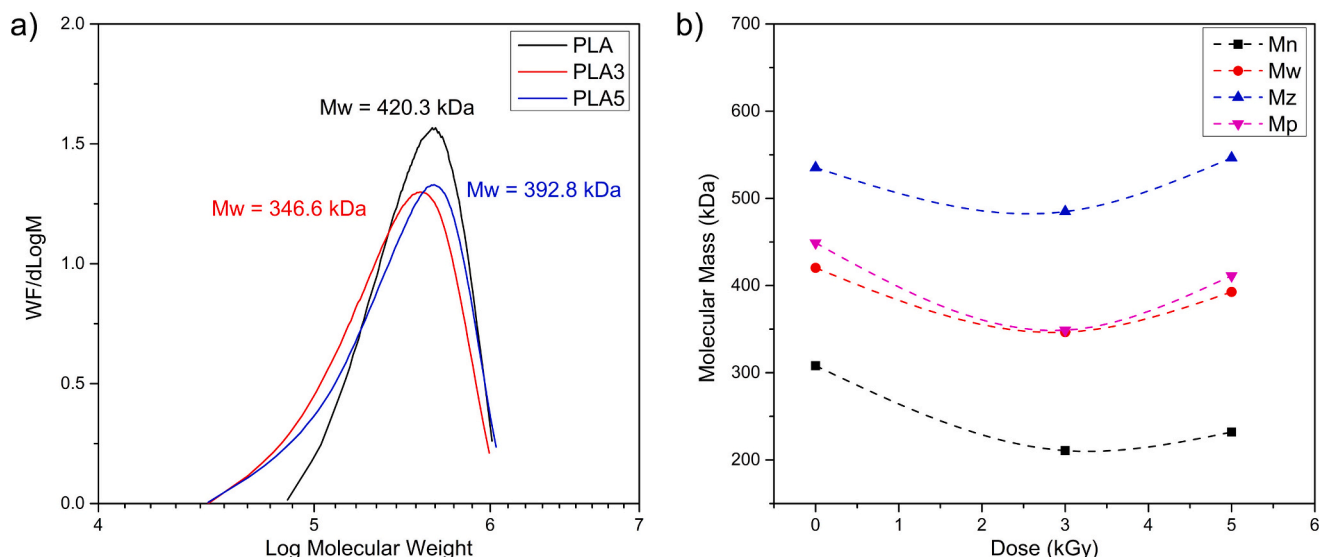


Fig. 2. Molar mass distributions of neat PLA and PLA subjected to gamma irradiation: (a) Wt/dLogM as a function of LogM; (b) behavior in different molecular weight averages.

Table 1

Molecular weight of neat PLA and PLA exposed to 3 kGy and 5 kGy of gamma irradiation.

Sample	Mn (kDa)	Mw (kDa)	Mz (kDa)	Mp (kDa)	D (Mw/Mn)
PLA	308.1	420.3	535.2	448.9	1.4
PLA3	210.8	346.6	484.9	348.8	1.6
PLA5	231.9	392.8	546.5	411.3	1.7

recombination or crosslinking, may begin to counterbalance the effect of chain scission at this dose. This is further evidenced by the behavior of the polydispersity index (D), which initially decreases at 3 kGy due to chain scission but increases again at 5 kGy, suggesting a broader molecular weight distribution likely resulting from branching or crosslinking [46]. Supporting evidence for this hypothesis comes from the rheological results that will be presented later, which showed an increase in complex viscosity, storage modulus, and loss modulus at 3 kGy, followed by a slight decline at 5 kGy. These trends could indicate the formation of long-chain branching. In contrast, at higher irradiation doses (e.g., 100–150 kGy), extensive chain scission dominates, resulting in substantial reductions in molecular weight and mechanical properties [36]. The behavior at lower doses mirrors this trend but to a much lesser extent, underscoring the sensitivity of PLA to gamma irradiation even at minimal exposure levels.

3.2. Tensile mechanical properties

The tensile mechanical properties of PLA, PBAT, and their blends with non-irradiated and low-dose irradiated PLA are shown in Fig. 3a–c and summarized in Table 2. The tensile modulus of PLA in this study (1.0–1.3 GPa) is lower than typical literature values (1.8–3.5 GPa [47–52]). This deviation can be attributed to processing parameters, such as injection pressure and temperature, mold temperature, moisture content, and the specific PLA grade used [50]. While PLA generally exhibits moderate stiffness and inherent brittleness, variations in experimental conditions commonly influence its mechanical response. Upon adding PBAT, the tensile modulus of the blend increased, this could be attributed to a synergistic effect related to induced crystallinity and interfacial interaction during processing. PBAT droplets can serve as nucleation sites for PLA crystallization during cooling, promoting a modest increase in PLA matrix crystallinity (~20% for neat blend by XRD). Given the strong dependence of PLA's stiffness on crystallinity,

even this small enhancement can offset the softening effect of the flexible PBAT phase, leading to a net increase in blend modulus [53].

By applying gamma irradiation, the results indicate that low-dose gamma irradiation significantly influences the mechanical performance of the PLA/PBAT blends. For neat PLA, a slight reduction in yield stress is observed after irradiation, likely due to minor chain scission. However, for PLA/PBAT blends, low-dose gamma irradiation of PLA prior to blending leads to an improvement in mechanical properties. Specifically, the PLA3/PBAT blend (PLA irradiated at 3 kGy) shows an increase in yield stress by 7.7%, elongation at break by 8.6% and tensile strength at break by 40.9% compared to the non-irradiated PLA/PBAT blend. PLA5/PBAT blend (PLA irradiated at 5 kGy) shows that improvements remain substantial but slightly less pronounced, with yield stress by 6.0% and elongation at break by 12.9%. The significant increase in ductility observed in the irradiated samples strongly supports the effectiveness of the compatibilization strategy employed in this work. This result aligns with the results reported by Raj et al. [54], who demonstrated that enhanced ductility in polymer blends (particularly PLA-based systems) is a key indicator of successful compatibilization. In their study, the authors attributed improved elongation at break to better interfacial adhesion facilitated by the compatibilizer, which enabled more efficient stress transfer between phases. Similarly, in our case, the rise in elongation at break following low-dose gamma irradiation suggests that radiation-induced reactive species promoted interfacial bonding between PLA and PBAT, thereby reducing phase separation and enhancing blend homogeneity. These improvements suggest that low doses of gamma irradiation promote a delicate balance between inducing chain scission and enhancing compatibilization. The limited chain scission generates free radicals within the PLA matrix, which can interact with PBAT chains, thereby improving interfacial adhesion and compatibility [55,56]. This contrasts with higher irradiation doses, where excessive chain scission often leads to embrittlement and degradation of mechanical properties [36].

Fig. 3d presents the stress-strain curves for PLA, PBAT, and their blends subjected to low irradiation doses. PLA exhibits high stress and initial modulus but low strain at break, characteristic of a rigid plastic. At these low doses, a slight reduction in yield stress is observed for PLA, likely due to minor chain scission caused by irradiation. Conversely, PBAT displays typical thermoplastic elastomer behavior, with a high strain at break exceeding 1000% and a low modulus. The stress-strain response of the 50/50 PLA/PBAT blend falls between that of the individual components, showing a distinct yield point followed by plastic

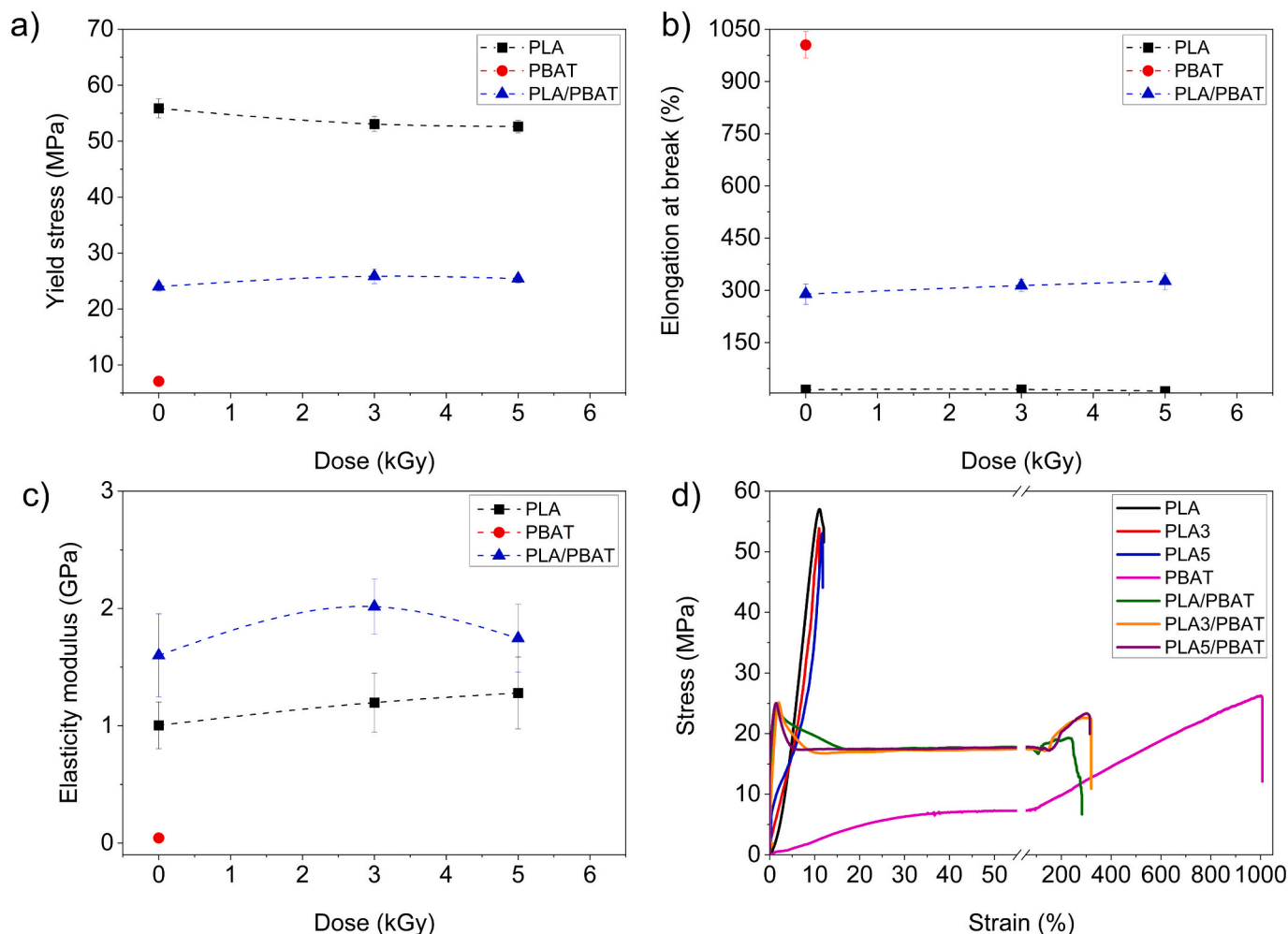


Fig. 3. Tensile mechanical behavior of PLA, PBAT, and PLA/PBAT blends: (a) yield stress; (b) elongation at break; (c) elasticity modulus; (d) stress-strain curves.

Table 2

Tensile properties of PLA, PBAT, and their blends, comparing samples where PLA was or was not subjected to gamma irradiation.

Sample	Yield stress (MPa)	Tensile modulus (GPa)	Yield strain (%)	Tensile strength at break (MPa)	Elongation at break (%)
PLA	55.88 ± 1.70	1.00 ± 0.20	11.62 ± 1.80	51.18 ± 2.94	14.70 ± 4.56
PLA3	53.08 ± 1.34	1.20 ± 0.25	14.89 ± 7.97	38.41 ± 10.13	14.99 ± 7.96
PLA5	52.62 ± 1.10	1.28 ± 0.31	8.00 ± 5.99	41.18 ± 7.39	10.25 ± 5.02
PBAT	7.10 ± 0.15	0.043 ± 0.005	47.51 ± 10.22	26.22 ± 1.60	1005.03 ± 38.12
PLA/PBAT	24.01 ± 0.77	1.60 ± 0.35	2.11 ± 0.48	13.34 ± 4.61	289.03 ± 28.90
PLA3/PBAT	25.86 ± 1.32	2.01 ± 0.23	1.76 ± 0.13	18.79 ± 4.05	313.79 ± 17.46
PLA5/PBAT	25.45 ± 0.77	1.74 ± 0.29	1.61 ± 0.43	17.85 ± 1.82	326.46 ± 24.77

elongation. The unirradiated blend exhibits irregularities during deformation, likely due to poor interfacial compatibility between the two phases. However, when exposed to low irradiation doses, these inconsistencies vanish, and the material shows improved strength and ductility. This improvement indicates that irradiation enhances interaction and bonding between PLA and PBAT phases, reducing heterogeneity and resulting in more uniform mechanical performance.

3.3. Scanning Electron Microscopy (SEM)

SEM micrographs of the fractured surfaces (Fig. 4) provide visual evidence of the morphological changes induced by low-dose gamma irradiation. The non-irradiated PLA/PBAT blend typically exhibits a coarse phase-separated morphology with distinct spherical PBAT particles (marked by yellow arrows) dispersed in the continuous PLA

matrix, indicative of poor immiscibility. This phase distribution can be explained by the higher viscosity of PLA in comparison to PBAT during processing [57].

In contrast, blends containing PLA irradiated at low doses show a marked transformation in PBAT particle morphology. The spherical PBAT domains shift to increased and elongated (areas surrounded by dashed yellow lines), irregular droplets, and the distinction between the dispersed phase and the matrix becomes less apparent. The increase in PBAT droplet size with irradiation dose is intrinsically linked to the reduction in PLA matrix viscosity, resulting from radiation-induced macromolecular chain scission [36,58]. This reduction in matrix viscosity alters the viscosity ratio ($p = \eta_d / \eta_m$, where η_d is the viscosity of the dispersed phase (PBAT) and η_m is the viscosity of the matrix phase (PLA), as considered by the Taylor and Grace theory) [59]. With PLA irradiation, the matrix viscosity (η_m) decreases drastically, leading to an

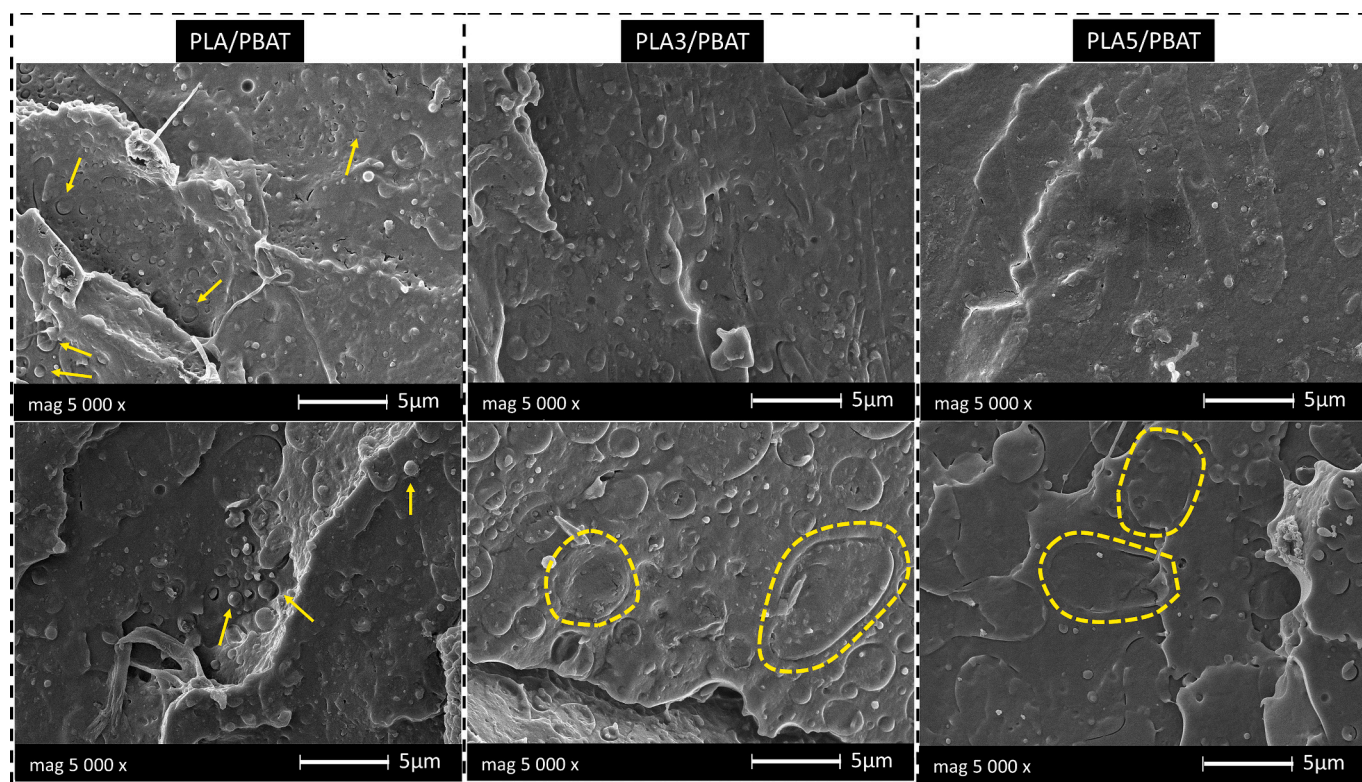


Fig. 4. SEM images of cryofractured samples revealing the morphology of PLA/PBAT blends incorporating PLA exposed to low irradiation doses.

increase in the viscosity ratio (p). This increase favors the growth of PBAT droplets through two main mechanisms: This elevated p hinders PBAT droplet fragmentation, as the less viscous PLA matrix transfers shear stress less effectively. Simultaneously, the lower matrix viscosity enhances system fluidity, promoting PBAT droplet mobility and collision frequency; combined with reduced resistance to droplet merging, this accelerates matrix degradation (which favors larger droplets for rheological reasons) and interfacial compatibilization (which stabilizes these droplets and improves blend integrity), consolidating gamma irradiation as an effective strategy for interface engineering in biodegradable polymer systems [62]. These results align with observations from higher-dose irradiation studies where the difference of the droplet size was also noted [36], but with the advantage that lower doses preserve material integrity while still promoting effective compatibilization.

Gamma irradiation compatibilization is frequently evidenced by improved stress transfer between phases, despite changes in dispersion morphology [61]. The formation of free radicals in irradiated PLA promotes active sites that, upon encountering PBAT chains during melt mixing, establish chemical bonds that anchor the phases [62]. Therefore, the behavior observed in SEM images reflects a balance between controlled matrix degradation (which favors larger droplets for rheological reasons) and interfacial compatibilization (which stabilizes these droplets and improves blend integrity), consolidating gamma irradiation as an effective strategy for interface engineering in biodegradable polymer systems [62]. These results align with observations from higher-dose irradiation studies where the difference of the droplet size was also noted [36], but with the advantage that lower doses preserve material integrity while still promoting effective compatibilization.

3.4. Attenuated Total Reflection – Fourier Transformed Infrared Spectroscopy (ATR-FTIR)

FTIR analysis of PLA and PLA/PBAT blends subjected to low doses of gamma irradiation reveals subtle but significant chemical changes (Fig. 5). For neat PLA, no new functional groups were detected, consistent with observations at higher irradiation doses [36]. However, an increase in the intensity of the O–H stretching band at 3301 cm^{-1} and –CH stretching bands at $2918\text{--}2850\text{ cm}^{-1}$ was noted. This indicates the formation of hydroxyl groups and chain scission, respectively, suggesting that gamma irradiation promotes oxidation and generates terminal hydroxyl and carboxyl groups even at low doses [63]. A small

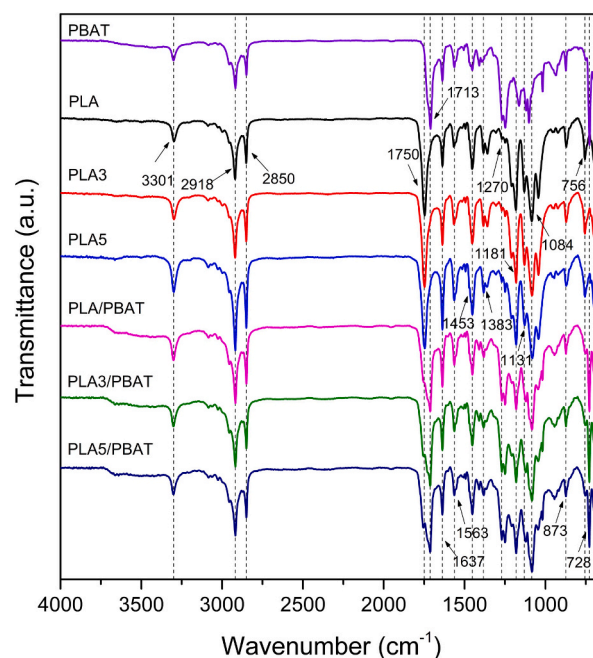


Fig. 5. FTIR spectra for PLA, PBAT, and PLA/PBAT blends.

increase in the intensity of bands at 1637 cm^{-1} and 1563 cm^{-1} , attributed to C=C double bonds [64], suggests the occurrence of recombination reactions during irradiation. Other characteristic peaks of PLA include: 1750 cm^{-1} (C=O stretching of oxidized chain ends), 1453 cm^{-1} and 1383 cm^{-1} (C–H bending vibrations of –CH₃ groups), 1270 , 1181 , 1131 , 1084 , and 1042 cm^{-1} (various C–O–C bond vibrations), 873 cm^{-1} (C–O–H groups), and 756 cm^{-1} (α-CH₃ wagging absorption).

For PLA/PBAT blends, the FTIR spectra showed similar trends, with

also no new functional groups emerging after irradiation. The characteristic peaks at 1750 cm^{-1} and 1713 cm^{-1} , corresponding to the $\text{C}=\text{O}$ stretching vibrations of PLA and PBAT, remained prominent. The peak at 1750 cm^{-1} (PLA's $\text{C}=\text{O}$ groups) exhibited a small increase with increasing irradiation dose, reflecting the generation of oxidized chain ends or terminal carboxyl groups [65]. This suggests that low doses of gamma irradiation could promote enhanced interfacial interactions and compatibility between PLA and PBAT, possibly through hydrogen bonding or other weak interactions, without causing extensive degradation or the formation of new chemical species. Conversely, the bands at 1637 cm^{-1} and 1563 cm^{-1} , associated with $\text{C}=\text{C}$ bonds, decreased in intensity, likely due to recombination reactions between reactive species in PLA and functional groups in PBAT, which could stabilize or mask double bonds. Lastly, bands at 873 cm^{-1} and 728 cm^{-1} were identified, corresponding to the out-of-plane bending vibrations of $=\text{C}-\text{H}$ groups in the benzene ring of PBAT.

3.5. X-ray diffraction (XRD)

XRD patterns of PLA irradiated at low doses confirm its predominantly amorphous nature (Fig. 6a), with a broad amorphous halo around $2\theta = 16^\circ$ (plane 200/110). No significant changes in crystallinity were observed for neat PLA, PLA at 3 kGy and 5 kGy, with crystallinity values of 12.6%, 12.1% and 12.7%, respectively. This suggests that low doses primarily induce mild chain scission without significantly altering the polymer's ability to form crystalline domains, contrasting with higher doses where more pronounced effects on crystallinity were reported [36]. Given that the material is highly amorphous, the peak deconvolution results should be regarded as approximate estimates. Additional details on the deconvolution procedure are provided in Fig. S1 and Table S1 of the Supplementary material.

PBAT demonstrates a semi-crystalline nature, as indicated by the presence of defined diffraction peaks at approximately 15.5° (plane 011), 16.7° (plane 010), 19.7° (plane 101), 22.4° (plane 100), 24.0° (plane 111), 28.5° (plane 104), and 30.4° (plane 104), as illustrated in Fig. 6b. The XRD pattern of PLA/PBAT blend showed strong similarities to that of neat PBAT. However, the addition of PLA to PBAT resulted in an expected increase in crystallinity. For the non-irradiated blend, a degree of crystallinity of 20.5% was observed. When subjected to low doses of gamma irradiation, the degree of crystallinity of the blends increased further, reaching 23.1% for 3 kGy dose and 28.5% for 5 kGy dose. This increase is attributed to the combined effects of chain scission and improved interfacial adhesion. Gamma irradiation induces chain scission in PLA, reducing intramolecular constraints and enabling greater chain mobility, which facilitates the formation of small

crystalline domains [66]. Additionally, the reactive sites created by chain scission may interact with PBAT, forming interphase regions that stabilize the blend's structure. These results highlight that low-dose irradiation can induce beneficial structural changes without the excessive degradation seen at higher doses [36].

3.6. Rheological properties

The rheological behavior of PLA and PLA/PBAT blends was investigated to understand the impact of low-dose gamma irradiation on their melt flow characteristics (Fig. 7). For neat PLA irradiated at low doses (3 and 5 kGy), a more pronounced reduction in complex viscosity was observed at lower frequencies compared to non-irradiated PLA. This decrease is consistent with chain scission reactions, which reduce the average molecular weight of the polymer chains, resulting in a reduction of viscosity within the Newtonian plateau region [67]. The storage modulus (G') and loss modulus (G'') also decreased, further supporting the occurrence of chain scission, but this reduction is confined to lower frequencies. At higher frequencies, its behavior closely mirrors that of unirradiated PLA. This frequency-dependent response contrasts with the effects of higher irradiation doses, where chain scission causes reductions in viscosity and modulus across all frequencies [36]. The limited changes at lower frequencies suggest that low-dose irradiation induces minor structural modifications, potentially linked to long-chain branching [68], consistent with GPC results. These alterations likely stem from free radical reactions triggered by irradiation, which may encourage chain recombination or crosslinking rather than extensive degradation. Such changes enhance the polymer's capacity to form entangled networks at lower frequencies while maintaining high-frequency characteristics typical of intact chains.

For PLA/PBAT blends, irradiation at 3 kGy leads to a slight increase in complex viscosity, storage modulus, and loss modulus across all frequencies, with more pronounced effects at lower frequencies. This suggests that gamma irradiation improves interfacial interactions between PLA and PBAT, fostering greater entanglement and compatibility [55,69]. The rise in storage modulus at lower frequencies further supports this, indicating enhanced elastic resistance, possibly due to stronger physical interactions or localized crosslinking at the interface. At 5 kGy, however, the rheological behavior of the blend becomes more similar to that of the unirradiated blend. A minor reduction in complex viscosity occurs at lower frequencies, while the storage modulus shows a slight increase. This indicates that competing mechanisms, such as chain scission, may counteract the benefits of improved compatibility at this dose. The subtle changes highlight the sensitivity of the blend's rheological properties to irradiation dose, underscoring the need for precise

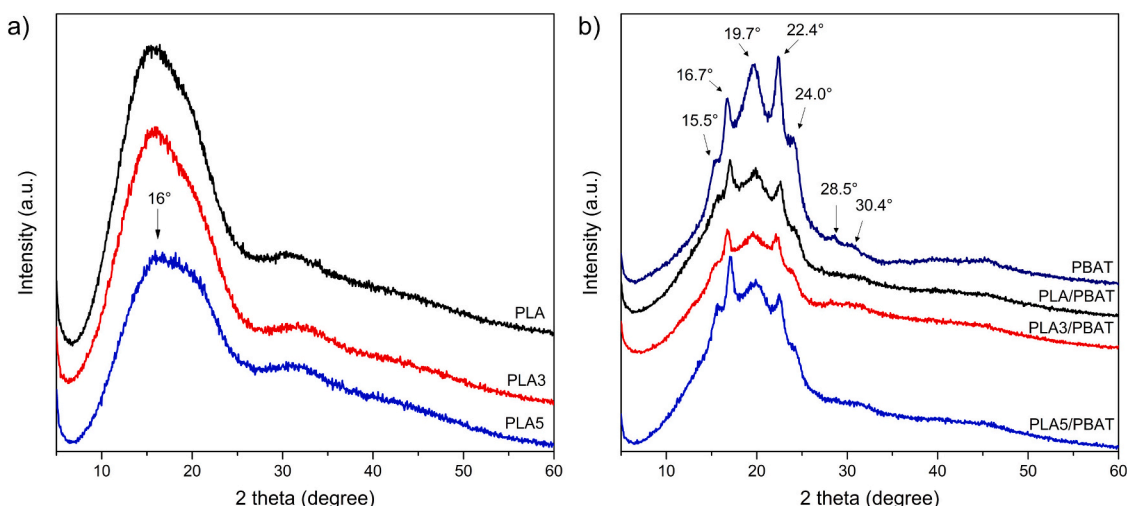


Fig. 6. XRD patterns for: (a) neat PLA and irradiated PLA; (b) PBAT and PLA/PBAT blends with different irradiation doses.

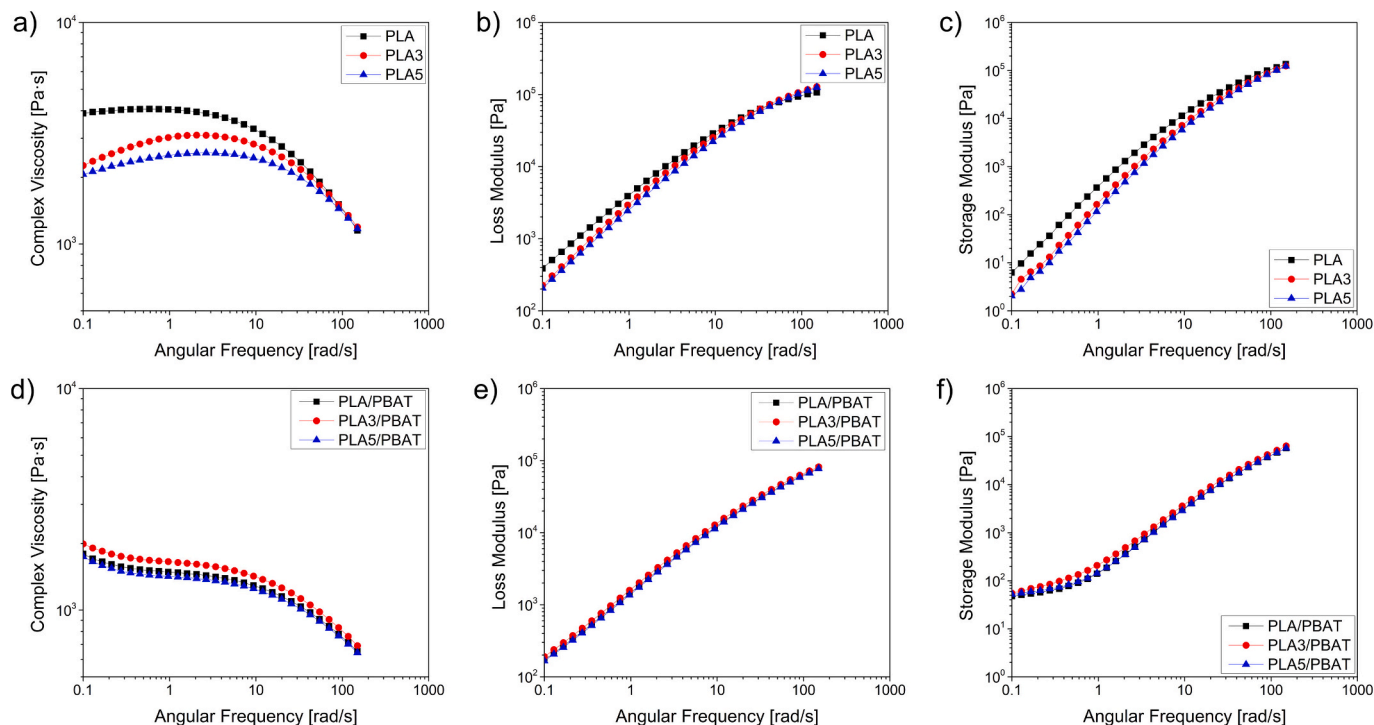


Fig. 7. Rheological properties: complex viscosity (a,d), loss Modulus (b,e) and storage modulus (c,f) as a function of angular frequency for PLA irradiated at different doses (a–c) and PLA/PBAT blends irradiated at different doses (d–f).

control.

3.7. Differential scanning calorimetry (DSC)

The thermal characteristics of PLA, PBAT, and their blends exposed to low doses of gamma irradiation were examined using differential scanning calorimetry. The results are summarized in Table 3 and illustrated in Fig. 8. DSC analysis of irradiated PLA showed a reduction in glass transition temperature (T_g) and a slight decrease in melting temperature (T_m) during the second heating cycle. The reduction in T_g suggests increased chain mobility due to chain scission and reduced molecular weight. Unlike higher irradiation doses, where melting peak split into distinct components due to the formation of shorter polymer chains [36], the melting peak for PLA at lower doses only broadens without complete separation. This indicates that while chain scission

occurs, it is insufficient to create well-defined populations of short chains detectable as separate melting peaks. As the irradiation dose increases from 3 to 5 kGy, the melting peak becomes slightly more pronounced, reflecting minor changes in crystalline structure or the emergence of smaller chain segments. However, the absence of significant peak splitting underscores the milder effects of lower-dose irradiation compared to the extensive degradation seen at higher doses. The difference between the crystallinity values obtained by DSC (1.0–1.5%) and XRD (12.1–12.7%) for PLA samples arises from the fundamental differences between the two techniques. DSC measures thermodynamic crystallinity based on melting and cold crystallization enthalpies, and the near-absence of a distinct cold crystallization peak indicates that the material is essentially amorphous in its initial state [70,71]. In contrast, XRD detects structural ordering, including short-range molecular arrangements, and the 12.6% value reflects an estimate derived from

Table 3

DSC thermal properties of PLA, PBAT and their blends with PLA irradiated at different doses during cooling and second heating cycle.

Sample	T_g^a (°C)	T_{hc}^b (°C)	ΔH_{hc}^c (J/g)	T_{m1}^d (°C)	T_{m2}^e (°C)	ΔH_m^f (J/g)	T_{cc}^g (°C)	ΔH_{cc}^h (J/g)	$X_{C,DSC}^{PLA,i}$ (%)	$X_{C,DSC}^{PBAT,j}$ (%)	$X_{C,XRD}^k$ (%)
PLA	59.6	–	–	153.9	–	1.2	–	–	1.3	–	12.6
PLA3	53.2	–	–	153.1	–	1.0	–	–	1.0	–	12.1
PLA5	53.0	–	–	153.5	–	1.4	–	–	1.5	–	12.7
PBAT	–	–	–	120.1	–	16.7	44.0	16.1	–	–	49.8
PLA/PBAT	54.7	122.0	5.1	150.2	–	8.6	81.0	6.3	5.0	4.1	20.5
PLA3/PBAT	54.4	116.5	10.7	149.2	–	15.1	74.9	6.1	19.5	15.9	23.1
PLA5/PBAT	54.5	116.9	9.1	149.1	–	13.2	72.6	6.6	14.1	11.5	28.5

^a Glass transition temperature.

^b Hot crystallization temperature.

^c Hot crystallization enthalpy.

^d First peak of melting temperature.

^e Second peak of melting temperature.

^f Melting enthalpy.

^g Cold crystallization temperature.

^h Cold crystallization enthalpy.

ⁱ Degree of crystallinity from DSC of PLA.

^j Degree of crystallinity from DSC of PBAT.

^k Degree of crystallinity from XRD.

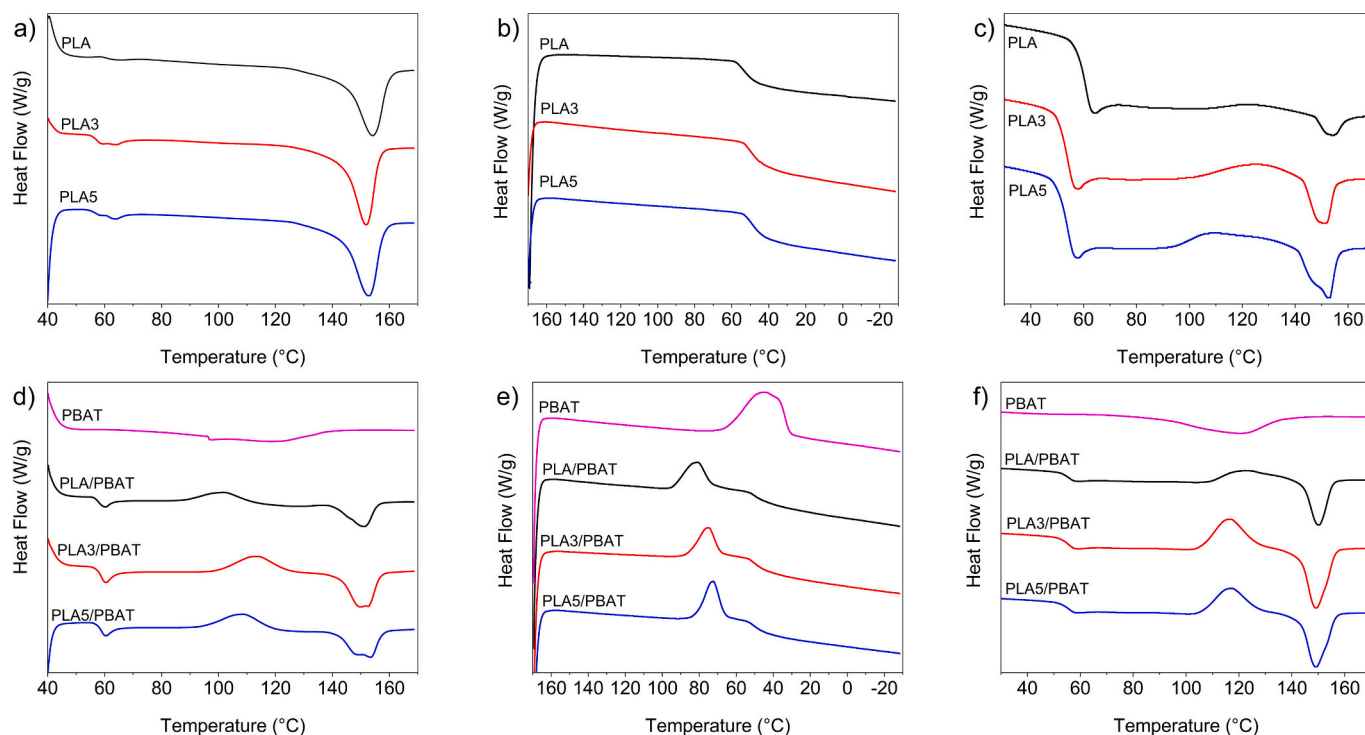


Fig. 8. DSC curves of first heating scan (a,d), cooling from the melt (b,e), second heating scan (c,f) for PLA irradiated at different doses (a–c) and PBAT and PLA/PBAT blends irradiated at different doses.

deconvolution of a broad amorphous halo [72], potentially capturing mesophases or local ordering that lack the long-range periodicity required to produce a measurable thermal transition in DSC.

For PLA/PBAT blends irradiated at low doses, the presence of irradiated PLA promotes a more defined hot crystallization peak compared to the unirradiated blend, indicating that gamma irradiation facilitates PLA crystallization. This effect is possibly due to shorter PLA chains that crystallize more easily and enhanced interfacial interactions between PLA and PBAT. The degree of crystallinity in the blends increased with 3 kGy irradiation but showed a slight reduction at 5 kGy, although it remains higher than the one of the unirradiated blend. This implies that low-dose gamma irradiation modifies the amorphous phase of PLA, indirectly enhancing crystallization. A slight reduction in T_g is also observed for the blends, consistent with the behavior of neat PLA. Notably, the cold crystallization peak shifts to lower temperatures for both the blends and irradiated PLA, signaling improved chain mobility and easier crystallization processes. Unlike the broader melting behavior observed for neat PLA, the blends do not exhibit significant broadening or splitting of the melting peak, suggesting that small chain fragments generated by irradiation interact strongly with PBAT, potentially stabilizing the blend's thermal properties. These results emphasize that low-dose gamma irradiation can enhance the compatibility of PLA/PBAT blends while avoiding severe degradation and brittleness associated with higher doses.

3.8. Thermogravimetric analysis (TGA)

The thermal degradation behavior of PLA, PBAT, and their blends exposed to low doses of gamma irradiation were analyzed using thermogravimetric analysis. The results are summarized in Table 4 and illustrated in Fig. 9. For neat PLA, the application of lower irradiation doses (3 and 5 kGy) did not significantly alter its thermal stability. The onset degradation temperature (T_{onset}) and temperatures corresponding to 5% ($T_{5\%}$) and 50% ($T_{50\%}$) weight loss remained largely unchanged compared to unirradiated PLA. This indicates that low doses do not induce extensive chain scission or structural modifications that would

Table 4

TGA thermal properties of PLA, PBAT and their blends with PLA irradiated at low doses.

Sample	T_{onset} (°C)	$T_{5\%}$ (°C)	$T_{50\%}$ (°C)	$T_{DTG\ max}$ (°C)	$R_{600\ ^\circ C}$ (%)
PLA	332.9	329.3	363.8	370.5	0.4
PLA3	332.9	330.3	364.0	370.2	0.1
PLA5	332.9	329.8	363.7	370.8	0.2
PBAT	378.9	352.2	399.5	404.3	4.2
PLA/PBAT	328.6	319.2	377.0	354.8 / 403.5	1.5
PLA3/ PBAT	333.9	326.8	385.0	356.0 / 402.5	2.1
PLA5/ PBAT	330.9	326.5	371.5	359.7 / 405.0	2.0

compromise the thermal stability of PLA, contrasting with the significant reductions observed at higher irradiation doses [36]. However, a minor decrease in residual mass was noted for irradiated PLA, potentially indicating limited chain scission during irradiation.

For PLA/PBAT blends, a two-step degradation process was observed, reflecting the distinct thermal behaviors of PLA and PBAT. Interestingly, when PLA within the blend was irradiated at low doses, an increase in thermal stability was observed. The T_{onset} increased by 5.3°C for the blend irradiated at 3 kGy and by 2.3 °C for the blend irradiated at 5 kGy. $T_{5\%}$ also showed an increase, indicating enhanced thermal stability. This improvement is attributed to enhanced interfacial interactions between PLA and PBAT induced by gamma irradiation, leading to better compatibility and reduced phase separation, which stabilizes the blend's structure and delays degradation. The increased residual mass observed for irradiated blends further supports the formation of more stable structures or crosslinked networks at the interface. These results contrast sharply with results obtained at higher irradiation doses, where gamma irradiation caused a significant decline in thermal stability for both neat PLA and PLA/PBAT blends [36]. At higher doses, extensive chain scission and PLA fragmentation weakened the material, leading to lower T_{onset} and $T_{5\%}$ values. Conversely, lower doses appear to enhance the

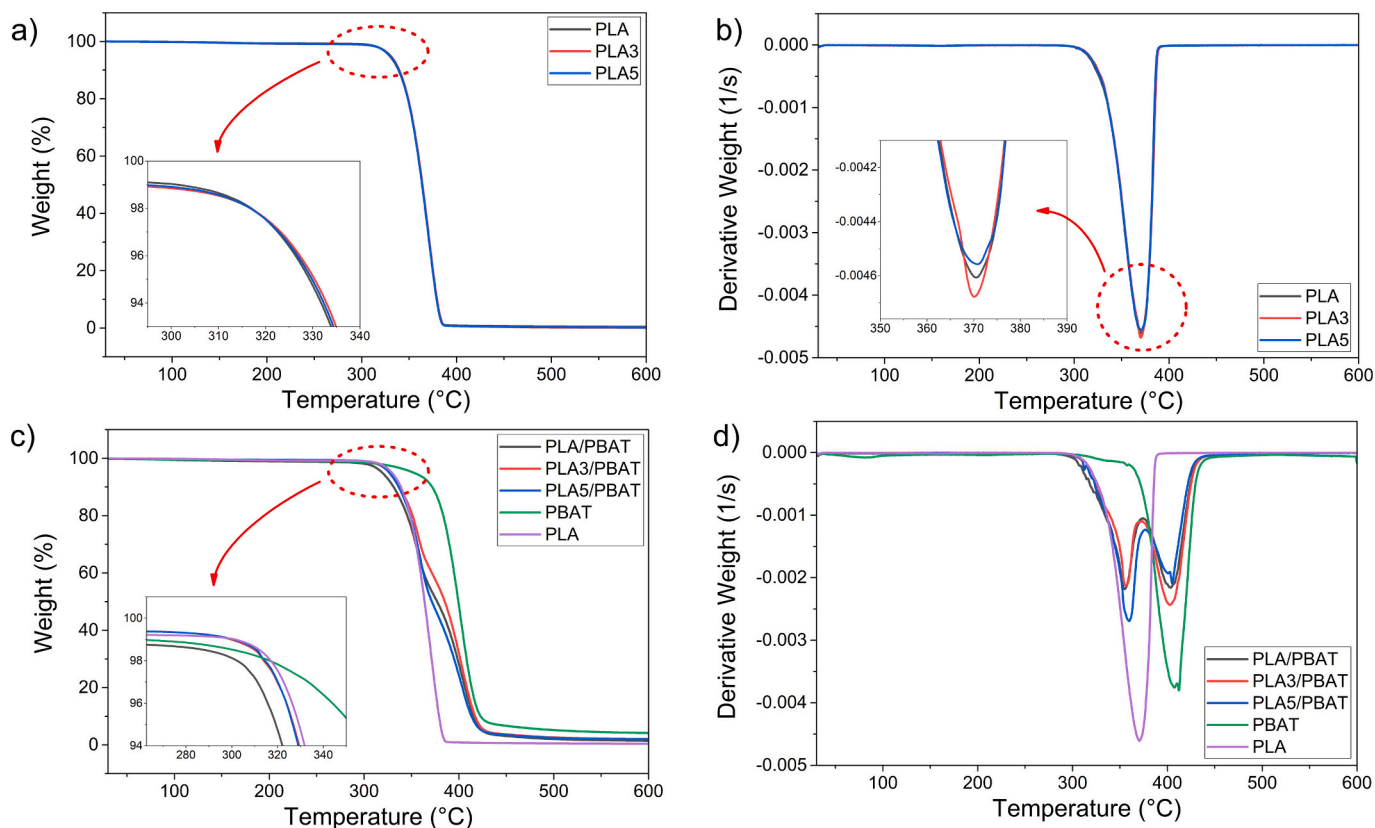


Fig. 9. (a,c) TGA and (b,d) DTG curves for PLA, PBAT and PLA/PBAT blends irradiated at different doses.

thermal stability of the blends by promoting favorable interactions without inducing severe degradation.

3.9. Dynamic mechanical analysis (DMA)

For PLA samples subjected to lower irradiation doses, measurements

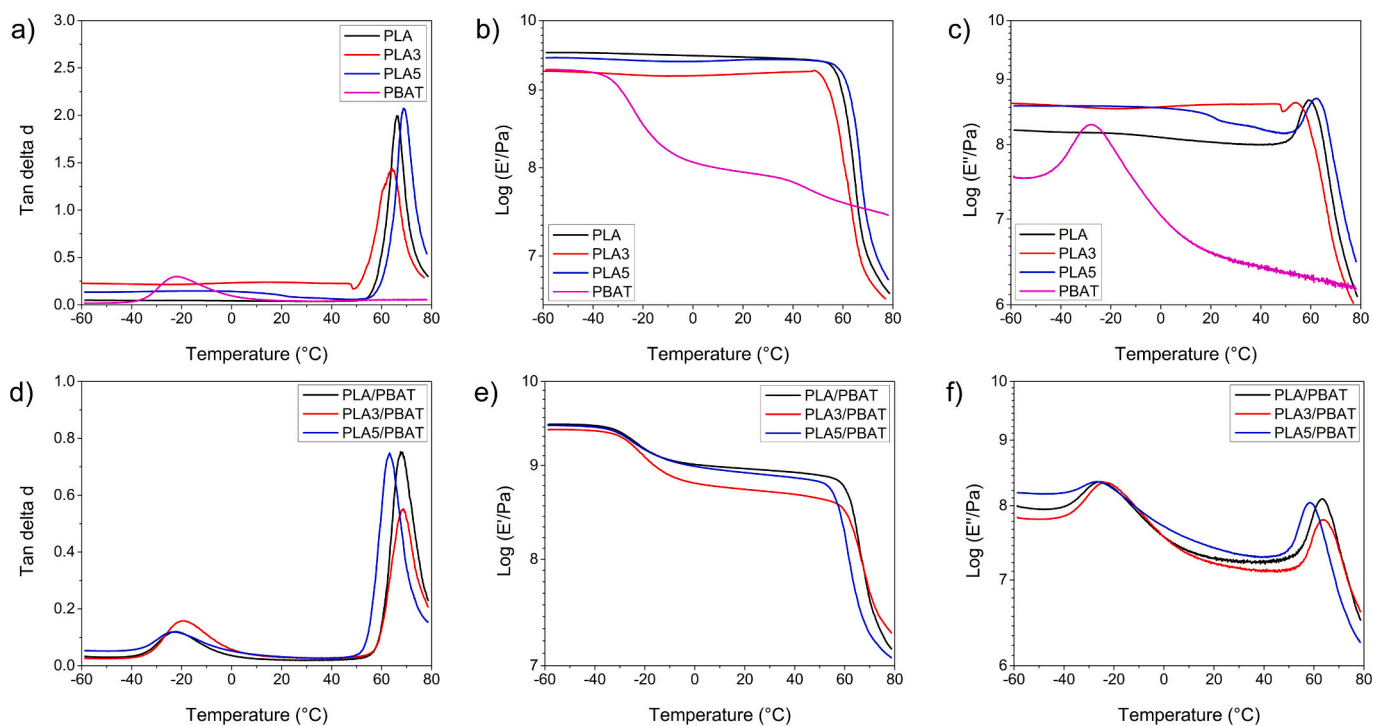


Fig. 10. DMA curves: (a,d) loss factor ($\tan\delta$), (b,e) storage modulus E' , (c,f) loss modulus E'' for PBAT and PLA irradiated at different doses (a-c) and for PLA/PBAT blends using PLA irradiated at different doses (d-f).

were feasible due to their reduced fragility compared to samples exposed to higher doses [37]. Fig. 10 presents the DMA curves for neat PBAT, PLA irradiated at varying low doses, and PLA/PBAT blends with different irradiation levels. In the case of neat PLA, the $\tan \delta$ peak, which corresponds to the glass transition temperature (T_g), shifts depending on the irradiation dose. At 3 kGy, the T_g of PLA decreases by 2.0 °C, indicating chain scission caused by gamma irradiation, as also observed in Table 5. This reduction in T_g reflects increased chain mobility resulting from the breakdown of polymer chains into shorter segments. Conversely, at 5 kGy, T_g increases by 2.6 °C, suggesting restricted chain movement. This behavior may be attributed to the formation of cross-links or recombination reactions between chains [73], supported by complementary analyses such as GPC and rheological studies.

The storage modulus of irradiated PLA also demonstrates dose-dependent behavior. At 3 kGy, the storage modulus decreases in the glass transition region (60–80 °C), potentially indicating a reduction in crystallinity [74]. This aligns with DSC results, where the degree of crystallinity (X_c) decreased at 3 kGy but slightly increased at 5 kGy. The decrease in crystallinity at 3 kGy may result from chain scission disrupting crystalline regions, while the subsequent increase at 5 kGy could stem from the recombination of free radicals within crystalline domains, promoting partial recovery of crystallinity. Similarly, the shift in the loss modulus peak to lower temperatures at 3 kGy and to higher temperatures at 5 kGy aligns with the trends observed in the $\tan \delta$ peak.

For PLA/PBAT blends, $\tan \delta$ curves reveal two distinct peaks corresponding to the T_g values of PLA and PBAT, indicating phase separation within the blend. The T_g values of PBAT and PLA in the unirradiated blend are −22.7 °C and 67.6 °C, respectively, resulting in a ΔT_g of 90.3 °C. However, for irradiated blends, the gap between the T_g values narrows to 88.3 °C and 86.0 °C for 3 kGy and 5 kGy, respectively. This reduction in ΔT_g suggests improved compatibility between PLA and PBAT [16,75], likely due to enhanced interfacial interactions facilitated by gamma irradiation. The compatibilization effect is further corroborated by rheological and thermal analyses, which demonstrated improved interfacial adhesion and changes in crystallization behavior in the irradiated blends. These results confirm that low-dose gamma irradiation fosters favorable interactions between the two phases, reducing phase separation and enhancing the blend's overall performance.

Additionally, the blend exposed to 3 kGy dose exhibits a significant reduction in both storage and loss modulus, while the blend irradiated at 5 kGy shows a smaller reduction, likely due to recombination effects at this dose. Regarding shape memory properties, lower irradiation doses yield results comparable to higher doses [37], as the difference in storage modulus between the two temperatures remains minimal.

4. Conclusion

This study successfully addressed the inherent immiscibility of 50/50 PLA/PBAT blends by employing low-dose gamma irradiation (3 and 5 kGy) of PLA prior to melt blending, a clean, solvent-free compatibilization strategy that bypasses the cost, complexity, and potential environmental concerns of conventional chemical additives. Controlled chain scission induced in PLA generated reactive radicals and shorter chain segments that acted as compatibilizers during melt extrusion. This mechanism led to a marked morphological refinement, transitioning the blend from a coarse, phase-separated structure into a more homogeneous and interconnected morphology, indicative of enhanced interfacial adhesion.

These structural improvements directly translated into superior macroscopic performance: irradiated blends exhibited a simultaneous increase in yield stress (up to 7.7%), elongation at break (up to 12.9%) and tensile strength at break (up to +40.9%), demonstrating a balance between strength and ductility in an immiscible system. Notably, a clear enhancement in thermal stability, with the onset degradation temperature increasing by up to 5.3 °C for the 3 kGy irradiated blend, reversing the typical trend of radiation-induced degradation. Dynamic mechanical

Table 5

DMA thermal properties for PLA, PBAT and their blends with PLA irradiated at low doses.

Sample	T_{g1} (°C)	T_{g2} (°C)	ΔT_g (°C)	Storage modulus at 25 °C (MPa)	Storage modulus at 80 °C (MPa)
PLA	–	66.1	–	2859.41	4.12
PLA3	–	64.1	–	1703.23	3.63
PLA5	–	68.7	–	2680.06	5.68
PBAT	−22.1	–	–	84.85	27.94
PLA/ PBAT	−22.7	67.6	90.3	900.62	14.16
PLA3/ PBAT	−19.5	68.8	88.3	527.24	19.73
PLA5/ PBAT	−22.9	63.1	86.0	803.16	11.78

analysis showed a narrowing of the gap between the glass transition temperatures of the two phases, from 90.3 °C in the unirradiated blend to 86.0 °C at 5 kGy, signaling enhanced interfacial adhesion. Complementary XRD and DSC data indicated that the low-dose irradiation promotes crystallization, with the degree of crystallinity in the blends increasing from 20.5% to 28.5% (XRD) at 5 kGy. Critically, these gains were achieved without the extensive degradation typically associated with higher radiation doses, confirming that low-dose irradiation strikes an optimal equilibrium between interfacial activation and bulk property retention. As such, this approach significantly improves the viability of PLA/PBAT blends as high-performance, biodegradable alternatives to conventional plastics.

Nevertheless, this work was conducted at a laboratory scale using only two irradiation doses, and certain limitations remain. The long-term aging behavior, environmental degradation kinetics (e.g., soil, marine settings), and precise chemical nature of the PLA-PBAT interfacial reactions were not directly probed, conclusions were drawn primarily from indirect macroscopic and morphological evidence.

Therefore, future efforts should expand the dose range (e.g., 1–10 kGy) to map the full dose-property relationship and identify the optimum for compatibilization. Advanced spectroscopy techniques (e.g., XPS, solid-state NMR, or FTIR mapping) could provide direct molecular-level confirmation of interfacial grafting. Finally, studies on long-term stability, biodegradation profiles under realistic conditions, process scale-up, and comprehensive life-cycle assessment (LCA) are essential to validate the industrial and environmental potential of this promising technology.

CRedit authorship contribution statement

Fernanda Andrade Tigre da Costa: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alain Dufresne:** Writing – review & editing, Validation, Supervision, Formal analysis. **Duclerc Fernandes Parra:** Writing – review & editing, Validation, Supervision, Project administration, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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030-01).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ijbiomac.2026.152013>.

Data availability

Data will be made available on request.

References

- [1] UNEP, Plastic pollution. <https://www.unep.org/plastic-pollution>, 2025. (Accessed 13 October 2025).
- [2] UNEP, Global Trade Update (August 2025): Mobilising trade to curb plastic pollution. <https://unctad.org/publication/global-trade-update-august-2025-mobilising-trade-curb-plastic-pollution>, 2025. (Accessed 13 October 2025).
- [3] M. Dokl, A. Copot, D. Krajnc, Y. Van Fan, A. Vujanović, K.B. Aviso, R.R. Tan, Z. Kravanja, L. Čuček, Global projections of plastic use, end-of-life fate and potential changes in consumption, reduction, recycling and replacement with bioplastics to 2050, *Sustainable Prod. Consumption* 51 (2024) 498–518, <https://doi.org/10.1016/j.spc.2024.09.025>.
- [4] H. Ritchie, V. Samborska, M. Roser, Plastic pollution, *Our World in Data*, 2023. <https://ourworldindata.org/plastic-pollution>. (Accessed 13 October 2025).
- [5] H.S. Samuel, F.-D.M. Ekpan, M.O. Ori, Biodegradable, recyclable, and renewable polymers as alternatives to traditional petroleum-based plastics, *Asian Journal of Environmental Research* 1 (2024) 152–165, <https://doi.org/10.69930/ajer.v1i3.86>.
- [6] L.I. Vayshbeyn, E.E. Mastalygina, A.A. Olkhov, M.V. Podzorova, Poly(lactic acid)-based blends: a comprehensive review, *Appl. Sci.* 13 (2023) 5148, <https://doi.org/10.3390/app13085148>.
- [7] L. Ranakoti, B. Gangil, S.K. Mishra, T. Singh, S. Sharma, R.A. Ilyas, S. El-Khatib, Critical review on polylactic acid: properties, structure, processing, biocomposites, and nanocomposites, *Materials* 15 (2022) 4312, <https://doi.org/10.3390/ma15124312>.
- [8] T. Casalini, F. Rossi, A. Castrovinci, G. Perale, A perspective on Poly(lactic acid)-based polymers use for nanoparticles synthesis and applications, *Front. Bioeng. Biotechnol.* 7 (2019), <https://doi.org/10.3389/fbioe.2019.00259>.
- [9] X.-Y. Yu, H.-Y. Liu, M.-Y. Yan, F. Li, N.-W. Ke, G. Wu, S.-C. Chen, Y.-Z. Wang, Integration design of toughening agent for poly(lactic acid) with compatibility, transparency, and environmental friendliness, *ACS Appl. Polym. Mater.* 6 (2024) 5555–5565, <https://doi.org/10.1021/acsapm.4c00836>.
- [10] E.T.H. Vink, Karl.R. Rábago, D.A. Glassner, B. Springs, R.P. O'Connor, J. Kolstad, P.R. Gruber, The sustainability of NatureWorks™ polylactide polymers and Ingeo™ polylactide fibers: an update of the future, *Macromol. Biosci.* 4 (2004) 551–564, <https://doi.org/10.1002/mabi.200400023>.
- [11] E. Capuana, F. Lopresti, M. Ceraulo, V. La Carrubba, Poly-L-lactic acid (PLLA)-based biomaterials for regenerative medicine: a review on processing and applications, *Polymers* 14 (2022) 1153, <https://doi.org/10.3390/polym14061153>.
- [12] S. Farah, D.G. Anderson, R. Langer, Physical and mechanical properties of PLA, and their functions in widespread applications — a comprehensive review, *Adv. Drug Deliv. Rev.* 107 (2016) 367–392, <https://doi.org/10.1016/j.addr.2016.06.012>.
- [13] J. Jian, Z. Xiangbin, H. Xianbo, An overview on synthesis, properties and applications of poly(butylene adipate-co-terephthalate)-PBAT, *Adv. Ind. Eng. Polym. Res.* 3 (2020) 19–26, <https://doi.org/10.1016/j.aiepr.2020.01.001>.
- [14] Q. Zhang, M. Jiang, G. Wang, G. Zhou, Novel biobased high toughness PBAT/PEF blends: morphology, thermal properties, crystal structures and mechanical properties, *New J. Chem.* 44 (2020) 3112–3121, <https://doi.org/10.1039/C9NJ04861H>.
- [15] J. Ludwiczak, S. Frackowiak, K. Leluk, Study of thermal, mechanical and barrier properties of biodegradable PLA/PBAT films with highly oriented MMT, *Materials* 14 (2021) 7189, <https://doi.org/10.3390/ma14237189>.
- [16] X. Sui, X. Zhao, Z. Wang, S. Sun, Super-ductile and stiff PBAT/PLA biodegradable composites balanced with random PMMA-co-GMA copolymer as compatibilizer, *Polym. Int.* 72 (2023) 333–341, <https://doi.org/10.1002/pi.6471>.
- [17] R. Zhan, X.-L. Li, Y. Zheng, X.-R. Zeng, L.-Y. Shi, K.-K. Yang, Y.-Z. Wang, Fabrication of high-strength and tough PLA/PBAT composites via in-situ copolymer formation using an adaptable epoxy extender, *Int. J. Biol. Macromol.* 302 (2025) 140530, <https://doi.org/10.1016/j.ijbiomac.2025.140530>.
- [18] M. Bianchi, A. Dorigato, M. Morreale, A. Pegoretti, Evaluation of the physical and shape memory properties of fully biodegradable poly(lactic acid) (PLA)/poly(butylene adipate terephthalate) (PBAT) blends, *Polymers* 15 (2023) 881, <https://doi.org/10.3390/polym15040881>.
- [19] A.R. Ajitha, S. Thomas, Introduction, in: *Compatibilization of Polymer Blends*, Elsevier, 2020, pp. 1–29, <https://doi.org/10.1016/B978-0-12-816006-0.00001-3>.
- [20] X. Lu, R.A. Weiss, Relationship between the glass transition temperature and the interaction parameter of miscible binary polymer blends, *Macromolecules* 25 (1992) 3242–3246, <https://doi.org/10.1021/ma00038a033>.
- [21] S. Thomas, Y. Grohens, P. Jyotishkumar, *Characterization of polymer blends*, Wiley, 2014, <https://doi.org/10.1002/9783527645602>.
- [22] C. Aversa, M. Barletta, G. Cappiello, A. Gisario, Compatibilization strategies and analysis of morphological features of poly(butylene adipate-co-terephthalate) (PBAT)/poly(lactic acid) PLA blends: a state-of-art review, *Eur. Polym. J.* 173 (2022) 111304, <https://doi.org/10.1016/j.eurpolymj.2022.111304>.
- [23] W. Yu, Z. Hu, Y. Zhang, Y. Zhang, W. Dong, X. Li, S. Wang, Compatibilizing biodegradable poly(lactic acid)/polybutylene adipate-co-terephthalate blends via reactive graphene oxide for screw-based 3D printing, *Polymers* 15 (2023) 3992, <https://doi.org/10.3390/polym15193992>.
- [24] L.S.A. Andrade, E.O. da Silva, Effect of nanoparticles as reinforcements and compatibilizers of poly(Lactide)/poly(butylene adipate-co-terephthalate) blends for application in food packaging, *Polym. Adv. Technol.* 36 (2025), <https://doi.org/10.1002/pat.70298>.
- [25] A.R. Ajitha, S. Thomas, *Compatibilization of Polymer Blends*, Elsevier, 2020, <https://doi.org/10.1016/C2017-0-03891-0>.
- [26] B. Imre, B. Pukánszky, Compatibilization in bio-based and biodegradable polymer blends, *Eur. Polym. J.* 49 (2013) 1215–1233, <https://doi.org/10.1016/j.eurpolymj.2013.01.019>.
- [27] R.C. Nissa, A. Hanifah, E. Mardawati, P. Nugroho, M. Gozan, K. Kasbawati, B. Chen, Y. Nurhamiyah, Compatibility induced gamma radiation of agar/PBAT blends: impact on material properties, *Radiat. Phys. Chem.* 229 (2025) 112487, <https://doi.org/10.1016/j.radphyschem.2024.112487>.
- [28] C. Vasile, D. Pamfil, T. Zaharescu, R.-P. Dumitriu, G.M. Pricope, M. Răpă, G. Vasilievici, Effect of gamma irradiation on the PLA-based blends and biocomposites containing rosemary ethanolic extract and chitosan, *Polymers* 14 (2022) 1398, <https://doi.org/10.3390/polym14071398>.
- [29] C.M. Kavitha, K.M. Eshwarappa, S.C. Gurumurthy, N. Karunakara, I. Mallikarjun, Gamma radiation-induced modification in mechanical properties of hybrid PVA (go/ag)-based polymer nanocomposites, *Arab. J. Sci. Eng.* 49 (2024) 10137–10146, <https://doi.org/10.1007/s13369-024-08964-0>.
- [30] S.B. Charnley, Radiolysis, in: *Encyclopedia of Astrobiology*, Springer Berlin Heidelberg, Berlin, Heidelberg, 2023, p. 2618, https://doi.org/10.1007/978-3-662-65093-6_1344.
- [31] A.M. de Azevedo, P.H.P.M. da Silveira, T.J. Lopes, O.L.B. da Costa, S.N. Monteiro, V.F. Veiga-Júnior, P.C.R. Silveira, D.D. Cardoso, A.B.-H. da S. Figueiredo, Ionizing radiation and its effects on thermoplastic polymers: an overview, *Polymers* 17 (2025) 1110, <https://doi.org/10.3390/polym17081110>.
- [32] C. Vasile, G. Tantar, A. Creteanu, Recent insights into the research of (bio)active additives for advanced polymer materials, *Polymers* 17 (2025) 3139, <https://doi.org/10.3390/polym17233139>.
- [33] M.A. Elsayy, M. Fekry, A.M. Sayed, N.A. Maziad, G.R. Saad, Physico-chemical characteristics of biodegradable poly(lactic acid) and poly(lactic acid)/chitosan Nano-composites under the influence of gamma irradiation, *J. Polym. Environ.* 31 (2022) 2705–2714, <https://doi.org/10.1007/s10924-022-02693-x>.
- [34] R. Almasri, Y. Akiyama, Y. Manabe, F. Sato, A study on the prospects of vacuum gamma irradiation to enhance crosslinking for 3D-printing PLA/MCC biocomposite filaments, *Phys. Open* 15 (2023) 100154, <https://doi.org/10.1016/j.physo.2023.100154>.
- [35] F.A.T. da Costa, D.F. Parra, E.C.L. Cardoso, O. Güven, PLA, PBAT, cellulose nanocrystals (CNCs), and their blends: biodegradation, Compatibilization, and nanoparticle interactions, *J. Polym. Environ.* 31 (2023) 4662–4690, <https://doi.org/10.1007/s10924-023-02899-7>.
- [36] F.A.T. da Costa, E.C.L. Cardoso, A. Dufresne, D.F. Parra, Compatibilization of poly(butylene adipate-co-terephthalate)/polylactic acid blends by gamma radiation, *Polym. Bull.* 81 (2024) 14875–14902, <https://doi.org/10.1007/s00289-024-05428-1>.
- [37] F.A.T. da Costa, A. Dufresne, D.F. Parra, Impact of high-dose gamma irradiation on PLA/PBAT blends reinforced with cellulose nanoparticles from pineapple leaves, *ACS Omega* 10 (2025) 38182–38202, <https://doi.org/10.1021/acsomega.5c06115>.
- [38] P. Nugroho, H. Mitomo, F. Yoshii, T. Kume, Degradation of poly(L-lactic acid) by γ -irradiation, *Polym. Degrad. Stab.* 72 (2001) 337–343, [https://doi.org/10.1016/S0141-3910\(01\)00030-1](https://doi.org/10.1016/S0141-3910(01)00030-1).
- [39] T. Aouat, M. Kaci, J.-M. Lopez-Cuesta, E. Devaux, M. Mahlous, The effect of gamma-irradiation on morphology and properties of melt-spun poly (lactic acid)/cellulose fibers, *Polym. Degrad. Stab.* 160 (2019) 14–23, <https://doi.org/10.1016/j.polydegradstab.2018.11.014>.
- [40] Y. Zhou, M. Chen, X. Xu, Q. Meng, J. Tu, C. Ma, P. Xu, P. Wang, Y. Ding, Investigating the effects of γ -ray irradiation on the mechanical and dielectric properties of poly(lactide)/poly(butylene adipate-co-terephthalate)/carbon nanotubes composites, *Adv. Compos. Hybrid Mater.* 7 (2024) 45, <https://doi.org/10.1007/s42114-024-00859-w>.
- [41] A.T. Naikwadi, B.K. Sharma, K.D. Bhatt, P.A. Mahanwar, Gamma radiation processed polymeric materials for high performance applications: a review, *Front. Chem.* 10 (2022), <https://doi.org/10.3389/fchem.2022.837111>.
- [42] M.A. Dechet, A. Demina, L. Römling, J.S. Gómez Bonilla, F.J. Lanyi, D.W. Schubert, A. Bück, W. Peukert, J. Schmidt, Development of poly(L-lactide) (PLLA) microspheres precipitated from triacetin for application in powder bed fusion of polymers, *Addit. Manuf.* 32 (2020) 100966, <https://doi.org/10.1016/j.addma.2019.100966>.
- [43] American Society for Testing and Materials, *Standard Test Method for Tensile Properties of Plastics*, ASTM International, 2014, pp. 1–17.
- [44] American Society for Testing and Materials, *Standard Test Method for Transition Temperatures and Enthalpies of Fusion and Crystallization of Polymers by Differential Scanning*, ASTM International, 2012, pp. 1–7.

- [45] American Society for Testing and Materials, Standard Test Method for Compositional Analysis by Thermogravimetry, ASTM International, 2020, pp. 1–6, <https://doi.org/10.1520/E1131-20>.
- [46] H. Otaguro, L.F.C.P. de Lima, D.F. Parra, A.B. Lugão, M.A. Chinelatto, S. V. Canevarolo, High-energy radiation forming chain scission and branching in polypropylene, *Radiat. Phys. Chem.* 79 (2010) 318–324, <https://doi.org/10.1016/j.radphyschem.2009.11.003>.
- [47] H. Simmons, P. Tiwary, J.E. Colwell, M. Kontopoulou, Improvements in the crystallinity and mechanical properties of PLA by nucleation and annealing, *Polym. Degrad. Stab.* 166 (2019) 248–257, <https://doi.org/10.1016/j.polymdegradstab.2019.06.001>.
- [48] R.A. Wach, P. Wolszczak, A. Adamus-Wlodarczyk, Enhancement of mechanical properties of FDM-PLA parts via thermal Annealing, *Macromol. Mater. Eng.* 303 (2018), <https://doi.org/10.1002/mame.201800169>.
- [49] C.B.B. Luna, D.D. Siqueira, E.M. Araújo, R.M.R. Wellen, Annealing efficacy on PLA. Insights on mechanical, thermomechanical and crystallinity characters, *Momento* (2021) 1–17, <https://doi.org/10.15446/mo.n62.89099>.
- [50] S.C. Clarizio, R.A. Tataru, Tensile strength, elongation, hardness, and tensile and flexural moduli of PLA filled with glycerol-plasticized DDGS, *J. Polym. Environ.* 20 (2012) 638–646, <https://doi.org/10.1007/s10924-012-0452-3>.
- [51] V.L. Finkenstadt, C.-K. Liu, P.H. Cooke, L.S. Liu, J.L. Willett, Mechanical property characterization of plasticized sugar beet pulp and poly(lactic acid) green composites using acoustic emission and confocal microscopy, *J. Polym. Environ.* 16 (2008) 19–26, <https://doi.org/10.1007/s10924-008-0085-8>.
- [52] N.R. DiOrio, R.A. Tataru, K.A. Rosentrater, A.W. Otieno, Using DDGS in industrial materials, in: *Distillers Grains: Production, Properties, and Utilization*, 1st edition, AOCs Publishing, New York, 2012, pp. 429–448.
- [53] R. Al-Itty, K. Lamnawar, A. Maazouz, N. Billon, C. Combeaud, Effect of the simultaneous biaxial stretching on the structural and mechanical properties of PLA, PBAT and their blends at rubbery state, *Eur. Polym. J.* 68 (2015) 288–301, <https://doi.org/10.1016/j.eurpolymj.2015.05.001>.
- [54] A. Raj, C. Samuel, K. Prashantha, Role of compatibilizer in improving the properties of PLA/PA12 blends, *Front. Mater.* 7 (2020), <https://doi.org/10.3389/fmats.2020.00193>.
- [55] X. Wang, S. Peng, H. Chen, X. Yu, X. Zhao, Mechanical properties, rheological behaviors, and phase morphologies of high-toughness PLA/PBAT blends by in-situ reactive compatibilization, *Compos. Part B Eng.* 173 (2019) 107028, <https://doi.org/10.1016/j.compositesb.2019.107028>.
- [56] E.C.L. Cardoso, D.F. Parra, S.R. Scagliusi, R.M. Sales, F. Caviquioli, A.B. Lugão, Study of bio-based foams prepared from PBAT/PLA reinforced with bio-calcium carbonate and Compatibilized with gamma radiation, *Intechopen* (2019) 1–17, <https://doi.org/10.5772/intechopen.85462>.
- [57] N.T. Kilic, B.N. Can, M. Kodak, G. Ozkoc, Compatibilization of PLA/PBAT blends by using epoxy-POSS, *J. Appl. Polym. Sci.* 136 (2019) 47217, <https://doi.org/10.1002/app.47217>.
- [58] Y. Zhao, Q. Li, B. Wang, Y. Wang, C. Liu, C. Shen, Effect of electron beam irradiation dose on the properties of commercial biodegradable poly(lactic acid), poly(butylene adipate-co-terephthalate) and their blends, *Nucl. Inst. Methods Phys. Res. B* 478 (2020) 131–136, <https://doi.org/10.1016/j.nimb.2020.06.008>.
- [59] R. Al-Itty, K. Lamnawar, A. Maazouz, Rheological, morphological, and interfacial properties of compatibilized PLA/PBAT blends, *Rheol. Acta* 53 (2014) 501–517, <https://doi.org/10.1007/s00397-014-0774-2>.
- [60] M. Nofar, M.C. Heuzey, P.J. Carreau, M.R. Kamal, J. Randall, Coalescence in PLA-PBAT blends under shear flow: effects of blend preparation and PLA molecular weight, *J. Rheol.* 60 (2016) 637–648, <https://doi.org/10.1122/1.4953446>.
- [61] K. Yokoyama, Z. Guan, A Vitrimers acts as a Compatibilizer for polyethylene and polypropylene blends, *Angew. Chem. Int. Ed.* 63 (2024), <https://doi.org/10.1002/anie.202317264>.
- [62] X. Chen, Z. Zeng, Y. Ju, M. Zhou, H. Bai, Q. Fu, Design of biodegradable PLA/PBAT blends with balanced toughness and strength via interfacial compatibilization and dynamic vulcanization, *Polymer* 266 (2023) 125620, <https://doi.org/10.1016/j.polymer.2022.125620>.
- [63] A. Alsabbagh, R. Abu Saleem, R. Almasri, S. Aljarrah, S. Awad, Effects of gamma irradiation on 3D-printed polylactic acid (PLA) and high-density polyethylene (HDPE), *Polym. Bull.* 78 (2021) 4931–4945, <https://doi.org/10.1007/s00289-020-03349-3>.
- [64] T. Tosakul, P. Suetong, P. Chanthot, C. Pattamaprom, Degradation of polylactic acid and polylactic acid/natural rubber blown films in aquatic environment, *J. Polym. Res.* 29 (2022) 242, <https://doi.org/10.1007/s10965-022-03039-w>.
- [65] R. Malinowski, K. Moraczewski, A. Raszkowska-Kaczor, Studies on the uncrosslinked fraction of PLA/PBAT blends modified by electron radiation, *Materials* 13 (2020) 1–16, <https://doi.org/10.3390/ma13051068>.
- [66] Z. Zhudi, Y. Wenxue, C. Xinfang, Study on increase in crystallinity in γ -irradiated poly(vinylidene fluoride), *Radiat. Phys. Chem.* 65 (2002) 173–176, [https://doi.org/10.1016/S0969-806X\(02\)00194-9](https://doi.org/10.1016/S0969-806X(02)00194-9).
- [67] A.J. Satti, J.A. Ressa, M.L. Cerrada, N.A. Andreucetti, E.M. Vallés, Rheological analysis of irradiated crosslinkable and scissionable polymers used for medical devices under different radiation conditions, *Radiat. Phys. Chem.* 144 (2018) 298–303, <https://doi.org/10.1016/j.radphyschem.2017.09.002>.
- [68] Y. Wang, L. Yang, Y. Niu, Z. Wang, J. Zhang, F. Yu, H. Zhang, Rheological and topological characterizations of electron beam irradiation prepared long-chain branched polylactic acid, *J. Appl. Polym. Sci.* 122 (2011) 1857–1865, <https://doi.org/10.1002/app.34276>.
- [69] Y. Lyu, Y. Chen, Z. Lin, J. Zhang, X. Shi, Manipulating phase structure of biodegradable PLA/PBAT system: effects on dynamic rheological responses and 3D printing, *Compos. Sci. Technol.* 200 (2020) 108399, <https://doi.org/10.1016/j.compscitech.2020.108399>.
- [70] Y. Kong, J.N. Hay, The measurement of the crystallinity of polymers by DSC, *Polymer* 43 (2002) 3873–3878, [https://doi.org/10.1016/S0032-3861\(02\)00235-5](https://doi.org/10.1016/S0032-3861(02)00235-5).
- [71] N. Burgos, D. Tolaguera, S. Fiori, A. Jiménez, Synthesis and characterization of lactic acid oligomers: evaluation of performance as poly(lactic acid) plasticizers, *J. Polym. Environ.* 22 (2014) 227–235, <https://doi.org/10.1007/s10924-013-0628-5>.
- [72] Y.-T. Hsieh, S. Nozaki, M. Kido, K. Kamitani, K. Kojo, A. Takahara, Crystal polymorphism of polylactide and its composites by X-ray diffraction study, *Polym. J.* 52 (2020) 755–763, <https://doi.org/10.1038/s41428-020-0343-8>.
- [73] J. Davenas, I. Stevenson, N. Celette, S. Cambon, J.L. Gardette, A. Rivaton, L. Vignoud, Stability of polymers under ionising radiation: the many faces of radiation interactions with polymers, *Nucl. Inst. Methods Phys. Res. B* 191 (2002) 653–661, [https://doi.org/10.1016/S0168-583X\(02\)00628-6](https://doi.org/10.1016/S0168-583X(02)00628-6).
- [74] M. Mansouri, A. Berrayah, C. Beyens, C. Rosenauer, C. Jama, U. Maschke, Effects of electron beam irradiation on thermal and mechanical properties of poly(lactic acid) films, *Polym. Degrad. Stab.* 133 (2016) 293–302, <https://doi.org/10.1016/j.polymdegradstab.2016.09.005>.
- [75] B. Wang, Y. Jin, K. Kang, N. Yang, Y. Weng, Z. Huang, S. Men, Investigation on compatibility of PLA/PBAT blends modified by epoxy-terminated branched polymers through chemical micro-crosslinking, *E-Polymers* 20 (2020) 39–54, <https://doi.org/10.1515/epoly-2020-0005>.