



Original Article

Application of Gamma Irradiation for Recycling Waste Plastic Bag

Nguyen Van Tan^{1,*}, Nguyen Ngoc Duy², Le Anh Quoc¹,
Nguyen Chi Thuan¹, Dang Van Phu¹

¹*Research and Development Center for Radiation Technology,
Vietnam Atomic Energy Institute (VINATOM), Ho Chi Minh City, Vietnam*

²*Center for Nuclear Technologies, Vietnam Atomic Energy Institute (VINATOM), Ho Chi Minh City, Vietnam*

Received 13th July 2025

Revised 23rd September 2026; Accepted 08th October 2026

Abstract: This work conducted the application of gamma irradiation to enhance the mechanical and physico-chemical properties of waste plastic bags (WPBs) for recycling. WPBs pellets were irradiated at doses ranging from 10 to 30 kGy and characterized. Based on the recorded mechanical properties results, WPBs with a dose of 15 kGy was confirmed to be suitable for treating WPBs. Notably, the melting flow index, impact strength, and tensile strength of irradiated WPBs (iWPBs) reached ca. 70-80% of those of virgin PE. Furthermore, FTIR spectra analysis indicated that the irradiation doses above 15 kGy resulted in the formation of C=O and O-H groups, suggesting progressive degradation of the irradiated WPBs. This study demonstrated an efficient and environmentally friendly approach to recycling WPBs and reducing environmental impact.

Keywords: Waste plastic bag, gamma irradiation, recycling.

1. Introduction

The recycling of plastic waste is a significant global challenge, with common approaches including chemical, biological, and physical methods [1]. Ionizing radiation has emerged as a promising technique for recycling waste plastic materials to restore their physico-chemical and mechanical properties. This technology offers a potential avenue for

advancing environmentally friendly waste management strategies. Gamma-ray irradiation, as a material modification technique, offers advantages such as simplicity, scalability, and controllability [2]. In this study, gamma-ray irradiation was applied to enhance the physico-chemical and mechanical properties of waste plastic bags (WPBs) for recycling, representing one of the early applications of this method in Vietnam. Irradiated materials were analyzed and assessed for improvements in their properties. The application of gamma-ray irradiation to WPBs recycling is intended to reduce the environmental impact of plastic waste.

Corresponding author.

E-mail address: phu659797@yahoo.com

<https://doi.org/10.25073/2588-1140/vnunst.5918>

2. Experimental

2.1. Materials

WPBs, which were made of high density polyethylene (HDPE), were collected from post-consumer plastic waste sources in Ho Chi Minh City, Vietnam. The collected WPBs were sorted, washed with tap water to remove dirt and contaminants. The reference material was virgin polyethylene (Virgin PE), purchased from PTT Global Chemical Public Co., Ltd., Thailand with primarily HDPE component. The melting flow index (MFI) of the virgin PE was determined to be 0.34 g/10 min at 220 °C under a 2.16 kg load via ASTM D1238. Furthermore, its tensile strength, determined at a constant crosshead speed of 10 mm/min (as per ASTM D638), was 19 MPa with a corresponding tensile strain at break of 0.4.

2.2. Methods

The sorted and cleaned WPBs were cut into pieces ($\leq 2.0 \pm 0.5 \text{ cm}^2$) before being pelletized with the average dimension of $3.0 \pm 0.3 \text{ mm}$ using an MTH-SY130 (Maysun) machine (200 – 230 °C) at the University of Science. The pellets were then subjected to gamma-ray irradiation using an SVST-Co60/B industrial irradiator (dose rate $\sim 1 \text{ kGy/h}$) at doses of 10, 15, 20, 25, and 30 kGy at the Research and Development Center for Radiation Technology. The irradiated WPB pellets (120 g) were processed into plate form (iWPB) with the dimension of $15 \times 12.5 \times 2 \text{ mm}$ by mixing chamber and molding compress machine at 220 °C and 190 °C respectively for $\sim 15 \text{ min}$.

The properties of WPBs plate were determined by measuring the MFI via ASTM D1238, impact strength (IS) with ISO 179-2 Unnotched, tensile strength (TS) following ASTM D638, and Fourier-transform infrared spectroscopy (FTIR) via ASTM E1252.

2.3. Characterization

The MFI of the WPBs plate was measured via ASTM D1238 at 220 °C with a 2.16 kg

load, using a ZL-3014 plastometer. The final value was calculated as shown in Equation (1) [3]:

$$\text{MFI (T, m)} = \frac{600 \cdot m}{t} \quad (1)$$

Where m (g) is the average weight sample after cut, and t (s) is time cut. The test was repeated in triplicate to calculate an average MFI result.

The IS of the WPBs plate was determined on a YM-J0301 equipment per ISO 179-2 (Unnotched). The reported value, calculated via Equation (2) [4], was the mean of three replicate test.

$$\text{IS (kJ/m}^2\text{)} = \frac{W_b \cdot 10^3}{h \times b} \quad (2)$$

Where W_b (J) is energy absorbed to test specimen complete break, h (mm) is the specimen thickness, b (mm) is the specimen width.

Additionally, the tensile properties of test specimen, including tensile stress and tensile strain were tested by YM-H4202-H02 following ASTM D638 at a pulling speed of 10 mm/min with equation (3), (4) [5] and repeated quintuplicates.

$$\sigma = \frac{F}{b \times h} \quad (3)$$

Where σ (MPa) is tensile stress, F (N) is break load, h (mm) is the thickness of specimen, b (mm) is the width of specimen.

$$\varepsilon = \frac{\Delta L}{L_0} \quad (4)$$

With ε is tensile strain, ΔL (mm) is the change in length, L_0 (mm) is the initial gauge length.

The chemical structure change of the non-iWPB and iWPB samples were analyzed using an FTIR 8400S spectrometer (Shimadzu, Japan) via ASTM E1252 [6]. For each sample, spectra were recorded after 42 scans.

3. Results and Discussion

3.1. The Effect of Irradiation to Prepare WPBs

Figure 1 illustrated the process of WPBs preparation and irradiation. The experiment from this procedure showed the impact of gamma irradiation on the characteristics of the WPBs. Notably, the plate samples from irradiated WPB (iWPB) exhibited a reduced air bubbles formation and presented a smoother

surface morphology relative to the plates of non-irradiated WPBs. This observation suggested that iWPBs possessed the melt homogeneity, which was indicative of improved processability and greater compatibility. This attribute was a significant factor for the potential of gamma irradiation on WPBs and the application of recycled WPBs with another recycled/virgin polymers.

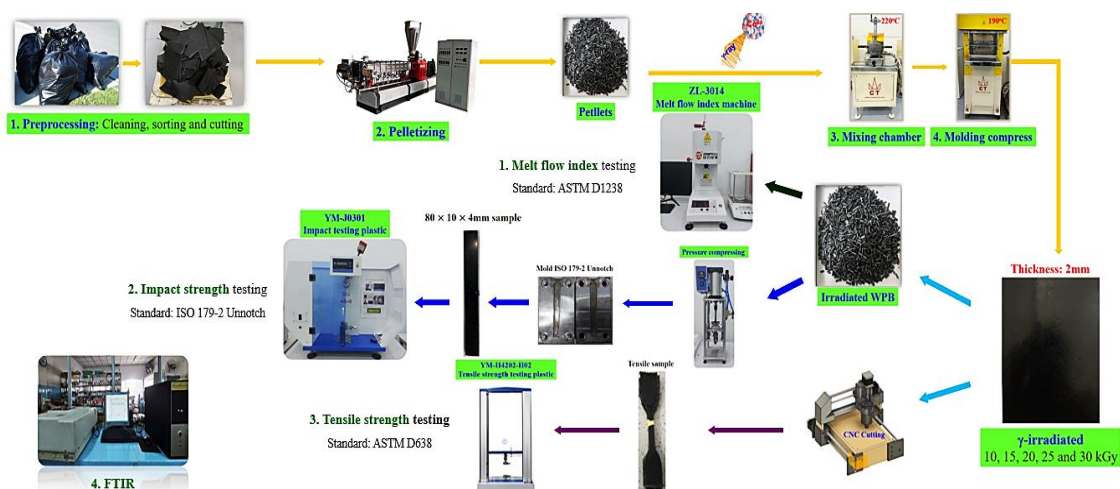


Figure 1. The preparation and irradiation of WPBs process.

3.2. The Effect of dose on MFI Property

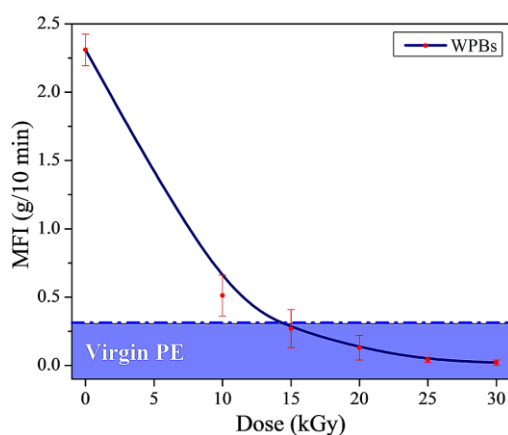


Figure 2. The MFI of WPBs via doses.

Figure 2 showed the influence of irradiation dose on the MFI of WPBs material. The MFI of the samples indicated a clear dose-dependent decrease.

The non-irradiated WPB exhibited a relatively high MFI of approximately 2.3 g/10 min, indicating its lower melt viscosity and molecular weight. As the dose of gamma irradiation increased, the MFI showed a consistent downward trend. Specifically, the MFI of iWPBs at 10 kGy decreased to ~ 0.5 g/10 min and showed a greater reduction at 15 kGy. At this dose, the MFI of the WPBs was found to be ~ 0.3 g/10 min, reflecting molecular weight increases in the polymer, which was remarkably comparable to the MFI of the virgin PE (ca. 0.3 g/10 min, indicated by the light blue region). M. Sirin et al., [7] reported that gamma irradiation-induced crosslinking progressively reduced chain and MFI of PE, which is consistent with the dose-dependent decrease in MFI observed in the present study. As the increasing dose reached 30 kGy, the MFI

continued to decline, indicating substantially increased mass.

The MFI similarity between irradiated WPBs at 15 kGy and virgin PE indicates that 15 kGy was an appropriate and effective dose for restoring the MFI of the WPBs. This finding highlighted that gamma irradiation as a potent approach for enhancing the MFI of WPBs, which could also change other physico-chemical properties of WPBs.

3.3. The Effect of dose on Impact Strength Property

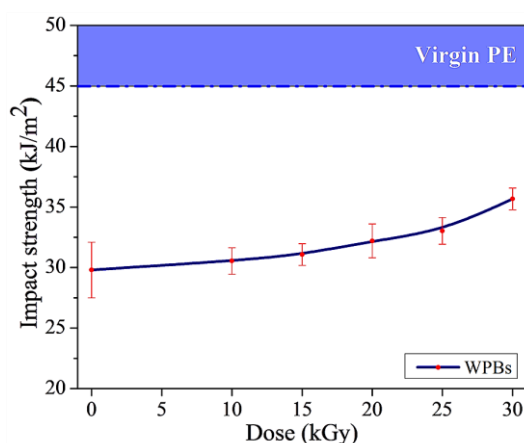


Figure 3. The impact strength of WPBs via doses.

Figure 3 presented the effect of dose on the impact strength of the WPBs. The non-irradiated WPBs had an impact strength of ~ 30 kJ/m². Generally, the impact strength of WPB tended to increase as the irradiation dose was raised. Specifically, the impact strength gradually rose from its initial value to approximately 31 kJ/m² at 15 kGy, and further increased to a peak of approximately 35 - 36 kJ/m² at the highest applied dose of 30 kGy. The dose-dependent improvement in impact strength of iWPBs is consistent with findings reported by H.A. Raslan et al., [8], where gamma irradiation-induced crosslinking progressively enhanced the impact resistance of irradiated polyethylene-based materials. However, the impact strength of the iWPB samples remained lower than that of virgin PE. Notably, the impact strength values at 15 kGy dose were quite similar to

those at other irradiation doses. Therefore, 15 kGy was still appropriate for increasing the impact strength of WPBs.

3.4. The Effect of dose on Tensile Strength

Figure 4 provided the changes in tensile properties, specifically tensile stress and tensile strain at break of the WPB samples, via doses. The non-irradiated WPB showed a tensile stress of 10.8 MPa and a tensile strain at break of 0.77. With increasing irradiation dose, the tensile stress progressively rose, reaching 15.5 - 18.8 MPa at 10 - 30 kGy, approaching that of virgin PE (~ 19 MPa). In contrast, the tensile strain continuously decreased from its initial high value, falling to 0.65 - 0.40 at 10 - 30 kGy, nearing with that of virgin PE (~ 0.40). The simultaneous increase in tensile stress and decrease in tensile strain at break with increasing irradiation dose observed in this study are in good agreement with findings reported by M. Sirin et al., [7] and H.A. Raslan et al., [8], where gamma irradiation-induced crosslinking progressively enhanced tensile strength while reducing the ductility of polyethylene-based materials. Considering the substantial improvement in tensile stress to 17 MPa while maintaining a tensile strain of 0.60, the 15 kGy dose was still considered sufficient for enhancing the mechanical properties of WPBs for recycling applications.

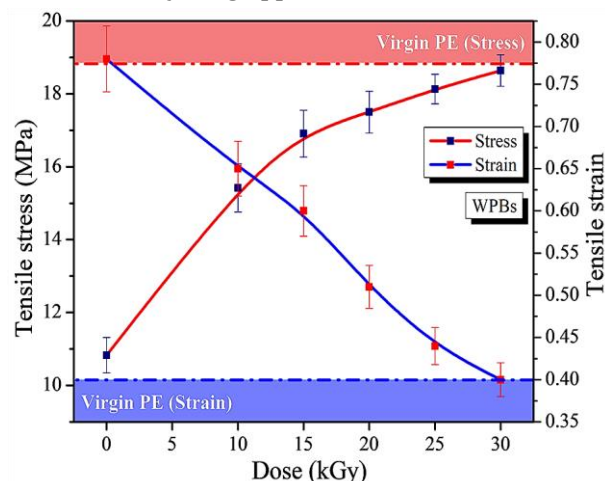


Figure 4. The tensile strength of WPBs via doses.

3.5. The Effect of dose on Structure Change

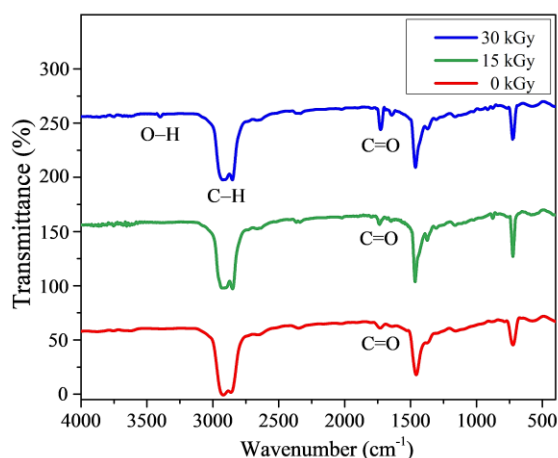


Figure 5. The FTIR of WPBs via doses.

Figure 5 presented the FTIR spectra of the WPBs samples before irradiation (red line), after irradiation at 15 kGy (green line), and 30 kGy (blue line) to investigate vibrational changes induced by gamma radiation. All spectra presented the characteristic absorption bands of PE. The spectrum exhibited strong absorption bands at 2915 - 2925 cm^{-1} and at 2845 - 2855 cm^{-1} , which were assigned to the asymmetric and symmetric -CH_2 stretching vibrations of the -CH_2 groups, respectively. Additionally, the -C-H bending vibrations of the -CH_2 groups showed at ca. 1460 - 1470 cm^{-1} , and a peak at ca. 720 - 730 cm^{-1} represented the -CH_2 rocking mode within the -CH_2 groups forming the polymer backbone structure. The study of H.E. Shim *et al.* [9] showed that the crystallinity of polyethylene corresponded to the absorption peak at 720 cm^{-1} , which was characteristic of the vibration of the -CH_2 group. As seen in Figure 5, the absorption peak increased in sharpness and intensity at the irradiation dose of 15 kGy, then decreased slightly at 30 kGy. It could be deduced that gamma irradiation at 15 kGy was a capable signal for increasing the crystallinity of polyethylene, as well as WPBs or recycled polymers. Besides, an absorption band of the -C=O group was already present at $\sim 1740 \text{ cm}^{-1}$, indicating a certain degree of pre-existing

oxidation in the WPBs (red line). Results of irradiated samples indicated that atmospheric conditions significantly affected the irradiation process. Specifically, the appearance of the -O-H band at 3400 cm^{-1} and the increased intensity of the -C=O peak (at $\sim 1740 \text{ cm}^{-1}$) signified oxidative degradation. This phenomenon was attributed to the presence of oxygen in atmosphere, which formed hydrogen peroxide ($\text{HO}_2^\bullet$) free radicals during irradiation. These radicals subsequently decomposed, leading to oxidative reactions and the formation of hydroxyl and carbonyl functional groups within the polymer. This hypothesis, first proposed by Tabb *et al.*, [10], was later confirmed by Wenxiu *et al.*, [11], who observed the characteristic -C=O band at 1716 cm^{-1} in air-irradiated samples. The mechanism was further demonstrated by comparing different environmental conditions. When an inert gas was used to replace the initial supply of dissolved oxygen, the FTIR spectra showed a marked decrease in the intensity of the -C=O band. Conversely, irradiation in air facilitated the continuous diffusion of atmospheric oxygen into the sample during the reaction. This was supported by the of Wenxiu *et al.*, who found that pre-treating PE samples in a vacuum for 12 hours eliminated the formation of oxygen-containing groups during irradiation, thereby proving the critical role of initial dissolved oxygen. Even with these changes, the fundamental PE structure remained largely intact. This suggested that a dose of 15 kGy was an appropriate selection for improving the physico-chemical properties and the crystallinity degree of WPBs, with limited impact on their functional group integrity.

3.6. Discussion

The investigation into the effects of gamma irradiation on WPBs revealed a significant influence on their physicochemical and mechanical properties. The findings suggested that these alterations were primarily governed by two competing mechanisms: radiation-induced cross-linking and chain scission or oxidative degradation. The interplay between

these phenomena dictated the ultimate material response. Specifically, the dominance of one mechanism over the other appeared to be contingent upon both the inherent characteristics of the polymer matrix and the specific irradiation parameters employed.

WPBs were prepared, irradiated, and characterized (Figure 1). Gamma-ray irradiation showed promising for enhancing the physico-chemical and mechanical properties of WPBs (Figure 2-5). The MFI decreased with increasing dose, falling below that of the virgin PE region value at doses above approximately 15 kGy. This decrease suggested the increased melt viscosity due to radiation-induced cross-linking [12]. When WPBs were irradiated in atmosphere, free radicals were formed on the polymer chains, which could react with each other to form cross-links between these polymer chains, resulting in the formation of a polymer network. The reduced melt flowability was attributed to the formation of a crosslink, which simultaneously increased the average molecular weight and limited the polymer chain flexibility. The similarity in MFI between WPB irradiated at 15 kGy and virgin PE (~ 0.3 g/10 min) showed that at this dose, the cross-linking mechanism was dominant and effective in restoring the processability of the material. This result was available from the findings of Moradkhani et al., [13] and could be similarly explained by the increased radiation-induced crosslinking within the polymer structure. Crosslinking led to an increase in the average molecular weight and the development of network structure, thereby impeding polymer chain flexibility and consequently reducing melt flowability.

Concurrently, the impact strength increased gradually with dose, approaching the value of virgin PE, which was a consistent tendency with that reported by Wang et al., [14]. This once again suggested that gamma irradiation could improve the impact strength through enhanced homogeneity during the sample preparation process, an effect facilitated by the formation of new intermolecular linkages between free radicals via radiation-induced

crosslinking. Similarly, the tensile strength also increased gradually, reaching nearly the value of virgin PE at doses of 10 - 30 kGy. The formation of new cross-links between polymer chains created a more stable network structure, which helped to dissipate stress more effectively and increased the resistance to deformation and fracture. The mechanical properties were influenced by a confluence of effects, such as increased cross-linking density, decreased crystallinity, and oxidative degradation of the polymer backbone when irradiated under atmospheric conditions [15]. While it was generally known that the tensile strength of various PE often decreased with increasing absorbed doses due to dominant chain scission, the observed improvement in this specific case could be attributed to radiation-induced cross-linking, which enhanced tensile strength at certain dose levels (such as 15 kGy). However, when the radiation dose surpassed the gel dose threshold (> 30 kGy), the material became excessively cross-linked and thus significantly stiffer. This increased stiffness led to a reduction in its strain capability (elongation at break) and required a greater force for breaking, ultimately resulting in a loss of the polymer's ductility. Regarding elongation at break, in the case of the PE studied, it increased. This could be explained by the fact that PE was a highly branched polymer; crosslinking occurred mainly between these branches, creating a rubber-like structure, which resulted in higher elongation at break. Overall, gamma-ray irradiation positively affected WPBs' properties within the 15 - 20 kGy range. However, since no significant improvement occurred beyond 15 kGy, and the 15 kGy sample reached approximately 70 - 90% of virgin PE properties, 15 kGy was considered suitable for WPBs recycling. This suggested the need to optimize the irradiation dose to achieve the desired balance of mechanical properties. Although chain cleavage could reduce mechanical properties, within the studied dose range, the cross-linking mechanism appeared to predominate or effectively balance the degradation process.

The comparison of FTIR spectra for WPBs irradiated at 0 (control), 15, and 30 kGy revealed characteristic PE absorptions (-C-H stretching; -CH₂ bending) in all samples. Notably, gamma radiation affected the crystallinity of PE polymer, most clearly shown by the change in -CH₂ rocking vibrations. Specifically, the absorption peak at 720 cm⁻¹ of the 15 kGy irradiated sample became sharper and had significantly higher intensity than that of the control sample. This increase was important indication that the crystallinity of the polymer was improved. Additionally, two other observations supported this interpretation: the intensity of the -C-H stretching vibrations decreased, and the MFI also decreased with increasing dose [12]. The combination of these results suggested that, although both crosslinking and scission (degradation) processes occurred during irradiation, the crosslinking polymer reaction played a primary role in this study. Therefore, the iWPB material might be better melty uniformity, improved processability, resulting in a smoother surface sample with fewer air bubbles. The polar groups might interact with each other or with other components in the blend, enhancing the compatibility and uniformity of the final product. These confirmed that gamma irradiation promoted the crosslinking effect, thereby increasing the crystallinity in the PE polymer structure. However, the samples irradiated at 15 and 30 kGy showed -C=O peaks (at ~1740 - 1710 cm⁻¹) and reduced -C-H intensity (at ~ 2918 cm⁻¹), indicating that oxidative degradation occurred. Furthermore, with increasing dose (>15 kGy), the intensity signals of -C=O and -O-H (at ~ 3400 cm⁻¹) increased [16]. As mentioned in the results section, this intensification of oxygen-containing groups was attributed to radiation-induced oxidative degradation, formed upon irradiation with atmospheric oxygen [17]. However, if oxidative degradation became too strong at high doses, it could weaken the mechanical properties, leading to brittleness and reduced ductility of the WPBs. It was important

to note that chemical structure changes could occur simultaneously as competitive phenomena when the dose changed. The chemical structure changes thus should be considered in the overall assessment of irradiation effects on WPBs. Despite these changes, the fundamental PE structure remained largely intact. Thus, gamma-ray irradiation offered a potential method for recycling WPBs, primarily through physical network changes rather than major chemical alterations.

4. Conclusion

Gamma-ray irradiation was a viable method for enhancing the properties of waste plastic bags (WPBs). An irradiation dose of approximately 15 kGy significantly enhanced the physico-chemical and mechanical properties of WPBs, achieving approximately 70 - 80% of the properties of virgin PE. These findings highlighted the potential of gamma-ray irradiation for recycling WPBs and other plastic waste, suggesting broader applications. However, large-scale implementation would require thorough cost-effectiveness analyses and government support.

Acknowledgements

This section devotes to acknowledge the equipment supports by the Research and Development Center for Radiation Technology, the GreenLab at the University of Science and LMS Technologies Vietnam Co., Ltd.

References

- [1] D. Peti, J. Dobránsky, P. Michalík, Recent Advances in Polymer Recycling: A Review of Chemical and Biological Processes for Sustainable Solutions, *Polym*, Vol. 17, No. 5, 2025, pp. 603.
- [2] H. M. Gayed, M. M. Ghobashy, Gamma Irradiation-enhanced Performance of Waste LLDPE Thermally Transformed into Advanced Sponge-like Material for Oil Decontamination, *Sci. Rep.*, Vol. 13, 2023, pp. 19128.

- [3] ASTM D1238 - Test Method for Melt Flow Rates of Thermoplastics by Extrusion Plastometer, ASTM International: West Conshohocken, PA, USA, 2013.
- [4] ISO 179-2 - Plastics - Determination of Charpy Impact properties - Part 2: Instrumented impact test, International Standard, Switzerland, 2020.
- [5] ASTM D638 - Test Method for Tensile Properties of Plastics, ASTM International: West Conshohocken, PA, USA, 2014.
- [6] ASTM E1252-98 - General Techniques for Obtaining Infrared Spectra for Qualitative Analysis, ASTM International: West Conshohocken, PA, USA, 2013.
- [7] M. Sirin, M. S. Zeybek, K. Sirin, Y. Abali, Effect of Gamma Irradiation on the Thermal and Mechanical Behaviour of Polypropylene and Polyethylene Blends, *Rad. Phys. Chem.*, Vol. 194, 2022, pp. 110034.
- [8] H. A. Raslan, M. Y. Elnaggar, E. S. Fathy, Effect of Gamma Irradiation on the Waste Polyethylene/bagasse Composites Reinforced with Flax and Sisal Fibers for use in Wood Applications, *J. Vinyl Addit. Technol.*, Vol. 30, No. 6, 2024, pp. 201-216.
- [9] H. E. Shim, B. M. Lee, D. H. Lim, Y. R. Nam, P. S. Choi, H. J. Gwon, A Comparative Study of Gamma-Ray Irradiation-Induced Oxidation: Polyethylene, Poly (Vinylidene Fluoride), and Polytetrafluoroethylene, *Polym (Basel)*, Vol. 14, No. 21, 2022, pp. 4570.
- [10] D. L. Tabb, J. Servcik, J. L. Koenig, Fourier Transform Infrared Study of the Effects of Irradiation on Polyethylene, *J. Polym. Sci. Polym. Phys. Ed*, Vol. 13, No. 4, 1975, pp. 815-824.
- [11] C. Wenxiu, J. Haishen, L. Xiangdi, L. Dongyuan, B. Huaying, On Polyethylene Film Dosimeter, *Rad. Phys. Chem.*, Vol. 16, No. 3, 1980, pp. 195-199.
- [12] 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.*, Vol. 10, 2022, pp. 1-15.
- [13] E. Moradkhani, M. Entezam, M. Ahmadi, H. A. Khonakdar, H. Ruckdäschel, V. Altstaedt, Irradiation Processing to Modify HDPE Molecular Architecture: Correlation with Irradiation Conditions and Polymer Grade, *Mater. Today Commun.*, Vol. 31, No. 1, 2022, pp. 1-9.
- [14] W. Wang, X. Zhang, Z. Mao, W. Zhao, Effects of Gamma Radiation on the Impact Strength of Polypropylene (PP)/high Density Polyethylene (HDPE) Blends, *Results Phys.*, Vol. 12, 2019, pp. 2169-2174.
- [15] L. Mészáros, Y. Kara, T. Fekete, K. Molnár, Development of Self-reinforced Low-density Polyethylene using γ -irradiation Cross-linked Polyethylene Fibres, *Rad. Phys. Chem.*, Vol. 170, 2020, pp. 1-6.
- [16] A. Massoud, N. A. Maziad, M. Othman, E. H. Borai, Estimation of Gamma Radiation Effects on the Polypropylene (PP) Films at Various doses, *J. Macromol. Sci, Part A*, Vol. 61, No. 12, 2024, pp. 1005-1018.
- [17] J. Zhang, V. Hirschberg, A. Goecke, M. Wilhelm, W. Yu, M. Orfgen, D. Rodrigue, Effect of Mechanical Recycling on Molecular Structure and Rheological Properties of High-density Polyethylene (HDPE), *Polym.*, Vol. 297, 2024, pp. 1-11.