



## EFFECTS OF GAMMA RADIATION ON THE MECHANICAL PERFORMANCE OF BIOPOLYMER MATERIALS

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**Abstract:** Gamma irradiation significantly influences the mechanical properties of the analyzed biocomposites, with the effects depending on the material composition. In this study, two biodegradable materials were used: Arboblend V2 Nature and Arbofill Fichte. Using a Type 2<sup>3</sup> experimental design, tensile and flexural test specimens were prepared from both the base granules and the granules irradiated with gamma rays at a dose of  $(28.7 \pm 1.4)$  kGy. The Arboblend V2 Nature material underwent pronounced degradation, showing reductions in flexural strength of approximately 55–60%, along with decreases in tensile strength and elongation at break, indicating embrittlement and degradation of the polymer structure. In contrast, Arbofill-Fichte exhibited more stable behavior, with moderate increases in mechanical strength of approximately 8–12%, while maintaining good deformability due to molecular crosslinking processes. Comparatively, Arbofill-Fichte demonstrates superior stability under gamma irradiation and greater potential for industrial applications and sterilization processes.

**Key words:** gamma irradiation, biopolymers, mechanical strength, molecular crosslinking, polymer degradation.

### 1. INTRODUCTION

In recent decades, interest in modifying the properties of polymeric materials through physical methods has increased considerably, particularly due to the need to develop materials with enhanced performance and reduced environmental impact. Among the methods used for polymer structure modification, gamma irradiation occupies an important position because of its ability to induce structural changes without the use of additional chemical additives. The action of gamma radiation on polymeric materials mainly leads to crosslinking and/or scission of macromolecular chains, with the final effects depending on the nature of the polymer, absorbed dose, irradiation atmosphere, and processing conditions, [1, 2].

Numerous studies have demonstrated that gamma irradiation can significantly influence the mechanical, thermal, structural, and morphological properties of polymers. Naikwadi and co-workers, [1] conducted an extensive analysis of the effects of gamma radiation on various categories of polymeric materials and highlighted that this method enables the improvement of properties such as thermal stability, mechanical strength, and interfacial compatibility in polymer composites. The authors also emphasized that the main disadvantage of the method is oxidative degradation and molecular weight reduction at high irradiation doses.

In the case of conventional polymers, gamma irradiation is frequently used for sterilization, structural modification, and enhancement of temperature and wear resistance. However, the effects produced in the material depend on the competition between crosslinking and molecular degradation processes. Yoshii and co-workers, [2] investigated the crosslinking of polycaprolactone (PCL) by gamma irradiation and observed that the treatment increased thermal stability and improved material strength. Nevertheless, the authors noted that a high degree of crosslinking may reduce the flexibility and biodegradability of the material.

In the context of current concerns regarding the reduction of pollution generated by conventional plastics, biodegradable polymeric materials have become an important alternative for numerous industrial applications. Polymers such as polylactic acid (PLA), polyhydroxybutyrate (PHB), polyhydroxybutyrate-co-valerate (PHBV), and polycaprolactone (PCL) are extensively studied due to their biodegradability and biocompatibility, [3]. However, their use is limited by certain disadvantages, such as high brittleness, thermal sensitivity, and low resistance to aging or sterilization.

Naser and co- authors, [3] highlighted that modifying the properties of biodegradable polymers through physical and chemical methods represents an important research direction for expanding their application fields. The authors showed that ionizing radiation treatments can improve certain functional characteristics of biopolymers; however, there is a risk of accelerated molecular structure degradation when high doses are applied.

Kijchavengkul and co- authors, [4] analyzed the effect of gamma irradiation on biodegradable PLA/P(VAc-co-VA) films intended for food packaging applications. The results showed that irradiation at moderate doses can maintain the mechanical and barrier properties of the material, enabling product sterilization without major structural modifications. However, the authors observed reduced flexibility and oxidative degradation at high irradiation doses.

Meddad and co- authors, [5] studied the behavior of gamma-irradiated PHBV/PLA blends in the presence of a compatibilizer and clay-based nanofillers. The study demonstrated that irradiation causes molecular weight reduction and morphological changes in the material due to polymer chain scission processes. The authors noted that the use of compatibilizers can partially reduce degradative effects, although the high sensitivity of PHBV and PLA to radiation remains an important limitation.

Bhat and co- authors, [6] investigated the thermal and mechanical properties of PLA materials modified by gamma irradiation in the presence of TAIC and OvPOSS crosslinking agents. The research demonstrated that irradiation can increase thermal stability and material rigidity through the formation of a crosslinked structure. At the same time, the authors emphasized that high doses promote degradation processes and reduce ductility.

Kaczmarek and co- authors, [7] analyzed the effects of gamma radiation on PLA filaments used in 3D printing technologies. The authors observed the formation of free radicals and significant structural modifications that influenced the mechanical and thermal properties of the material. Although the method enables sterilization and controlled modification of properties, the progressive degradation of polymer chains represents a disadvantage for long-term engineering applications.

Lee and co- authors, [8] studied the behavior of PLGA films subjected to gamma irradiation and concluded that the primary mechanism induced by radiation is the scission of macromolecular chains. This modification results in molecular weight reduction and accelerated degradation of the biodegradable material, particularly at high doses.

Islam and co- authors, [9] investigated biodegradable PCL/gelatin composites modified by gamma irradiation and reported improvements in thermomechanical properties and structural stability for certain irradiation doses. However, increasing the dose promoted reduced ductility and structural degradation of the composites.

Ali and co-workers, [10] analyzed the effect of gamma irradiation on biodegradable polystyrene/starch blends and showed that radiation treatment can improve compatibility between blend components. Nevertheless, pronounced degradation processes and reduced mechanical properties were observed at high doses.

Cieśla and co-authors, [11] studied biodegradable starch/PVA films irradiated with gamma radiation and highlighted changes in water absorption and material flexibility depending on the absorbed dose. The authors concluded that irradiation can contribute to the improvement of certain functional properties, although degradative effects become dominant at high doses.

Hossain and Islam, [12] carried out an analysis of biodegradable polymer composites modified by gamma irradiation and emphasized that changes in mechanical and thermal properties depend on the compatibility between the composite phases and the applied dose.

Clough, [13] analyzed the industrial applications of high-energy radiation on polymeric materials and showed that irradiation can lead to both crosslinking and molecular degradation, depending on the chemical structure of the material.

Rosiak and Yoshii, [14] highlighted the importance of ionizing radiation in obtaining polymeric materials used in biomedical applications, emphasizing the advantages of simultaneous sterilization and controlled structural modification.

Abdel Tawab and Orabi, [15] studied the influence of gamma radiation on biodegradable materials and concluded that high doses accelerate oxidative degradation and reduce the mechanical stability of polymers.

Torres-Giner, [16] analyzed current trends regarding the use of polyhydroxyalkanoates in biomedical and industrial applications, emphasizing the need to improve their properties through structural modification methods, including ionizing radiation.

Chapiro, [17] demonstrated that the radiochemical processes occurring in polymers under radiation exposure depend directly on molecular chain mobility and the presence of oxygen during irradiation.

Makuuchi and Cheng, [18] highlighted that polymer processing by irradiation represents an efficient method for improving functional properties, although controlling degradation remains a major challenge for biodegradable materials.

Charlesby, [19] analyzed the fundamental mechanisms of interaction between ionizing radiation and polymeric materials, showing that the balance between crosslinking and chain scission determines the final properties of the material.

Singh and Silverman, [20] emphasized that the use of gamma radiation for polymer modification offers important advantages regarding sterilization and processing without chemical additives; however, degradative effects may limit the use of sensitive biopolymers.

Overall, the studies reported in the literature show that the effects of gamma radiation on biodegradable materials are influenced by the chemical structure of the polymer, the presence of additives, and the value of the absorbed dose. In general, moderate doses promote crosslinking and the improvement of certain functional properties, whereas high doses lead to molecular degradation, embrittlement, and reduction of thermal and mechanical stability.

Based on the analyzed literature, it can be observed that most research is focused on conventional biodegradable polymers such as PLA (Polylactic Acid), PHBV (Poly(3-hydroxybutyrate-co-3-hydroxyvalerate)), and PCL (Polycaprolactone), while very limited information is available regarding the behavior of commercial lignocellulosic biodegradable materials such as Arboblend V2 Nature and Arbofill Fichte after exposure to gamma radiation.

In this context, the present research aims to evaluate the influence of gamma irradiation on the properties of biodegradable polymeric materials obtained by injection molding from granules irradiated before processing. The novelty of the study consists in investigating the behavior of Arboblend V2 Nature and Arbofill Fichte materials after gamma irradiation of the granules used for injection molding, thereby contributing to the development of knowledge regarding the use of biodegradable biomaterials in engineering and sustainable applications.

## 2. MATERIALS AND METHODS

The materials used in this study were Arboblend V2 Nature and Arbofill Fichte. These are biodegradable polymeric materials developed by Tecnar GmbH, obtained from renewable resources based on lignin, starch, and natural fibers, characterized by high biodegradability and a degradation rate comparable to that of wood under controlled natural conditions, [21–31].

The samples (for tensile and flexural tests) were produced by injection molding using an SZ-600H injection molding machine, with an 80 g capacity and a horizontal heating system.

The varied parameters were as follows: for Arboblend V2 Nature: melting temperature (160 and 170) °C, injection pressure (90 and 110) MPa, and injection speed (70 and 90) mm/s; and for Arbofill Fichte: melting temperature (145 and 155) °C, injection pressure (70 and 90) MPa, and injection speed (60 and 80) mm/s.

Tensile and bending tests were performed using a 100 kN VTS universal testing machine, according to the following testing standards: ASTM A370, ASTM E4, ASTM E9, ISO 6892, ISO 7438, ISO 7500-1, EN 10002-4, and GB/T 228-2002.

The two biodegradable materials were irradiated at the IRASM Department of IFIN-HH, Măgurele, Romania. An industrial type IV irradiator equipped with Co-60 gamma sources was used. Radiation processing was carried out in air at a room temperature of  $(25 \pm 2)$  °C, using a radiation dose of  $D = 28.7 \pm 1.4$  kGy for each material, Arbofill Fichte and Arboblend V2 Nature. The purpose of the radiation processing was to establish the tolerance limits of the materials in terms of radiation resistance, cross-linking, and degradation. The dose rate was approximately 2 kGy·h<sup>-1</sup>. The ethanol–chlorobenzene (ECB) dosimetry system was used to determine the applied dose and dose uniformity according to ISO/ASTM 51538.

## 3. RESULTS AND DISCUSSION

### 3.1 Tensile test

#### 3.1.1 Comparison between virgin Arboblend V2 Nature and gamma-irradiated Arboblend V2 Nature

The experimental data presented in Table 1 highlight the significant influence of gamma irradiation on the mechanical properties of the Arboblend V2 Nature material. Compared to the virgin material, the irradiated samples exhibit a noticeable reduction in both tensile strength and plastic deformation capacity.

Analyzing the average values obtained for each experimental set, it can be observed that the tensile strength of

the non-irradiated material generally falls within the range of approximately (18–36) MPa, whereas for the irradiated material, the values frequently decrease to the range of (9–19) MPa. In certain cases, the reduction exceeds (40–50) %, indicating significant structural degradation of the polymer matrix after radiation exposure. Furthermore, the variability of the experimental values for the irradiated samples suggests the occurrence of non-uniform structural modifications within the material bulk.

Table 1. Comparison between Base Arboblend V2 Nature and Gamma-Irradiated Arboblend V2 Nature

		base Arboblend		irradiated Arboblend	
	Sample	Strength (MPa)	Elongation (%)	Strength (MPa)	Elongation (%)
Exp. 1	1	5.87	0.34	12.69	0.73
	2	7.79	0.44	5.76	0.32
	3	6.53	0.46	13.58	0.84
<i>Average</i>		6.73±0.98	0.41±0.06	10.68±4.28	0.63±0.27
Exp. 2	1	20.56	1.3	12.00	0.72
	2	22.83	1.35	6.24	0.37
	3	12.20	0.70	10.23	0.60
<i>Average</i>		18.53±5.60	1.12±0.36	9.49±2.95	0.56±0.18
Exp. 3	1	16.80	1.07	16.74	1.03
	2	18.69	1.18	14.07	0.88
	3	18.98	1.16	12.43	0.72
<i>Average</i>		18.16±1.18	1.14±0.06	14.41±2.18	0.88±0.16
Exp. 4	1	20.94	1.22	15.63	0.97
	2	19.60	1.13	15.64	0.94
	3	21.62	1.46	9.72	0.56
<i>Average</i>		20.72±1.03	1.27±0.17	13.66±3.42	0.82±0.23
Exp. 5	1	29.86	1.98	3.98	0.39
	2	28.19	1.78	9.25	0.61
	3	36.46	2.56	18.00	1.69
<i>Average</i>		31.50±4.37	2.11±0.41	10.41±7.08	0.90±0.70
Exp. 6	1	37.29	2.58	7.50	0.50
	2	34.87	2.43	8.62	0.59
	3	35.48	2.33	12.87	0.97
<i>Average</i>		35.88±1.26	2.45±0.13	9.66±2.83	0.69±0.25
Exp. 7	1	32.11	2.13	20.16	1.37
	2	38.09	2.65	18.50	1.17
	3	38.62	2.70	18.21	1.16
<i>Average</i>		<b>36.27±3.62</b>	<b>2.49±0.32</b>	<b>18.96±1.05</b>	<b>1.23±0.12</b>
Exp. 8	1	29.50	1.86	17.00	1.23
	2	32.62	2.19	10.00	0.70
	3	34.65	2.38	20.12	1.48
<i>Average</i>		32.26±2.59	2.14±0.26	15.71±5.18	1.14±0.40

Figure 1 shows that gamma irradiation significantly reduces the elongation of the material, suggesting an increase in material brittleness. The stress–strain curves confirm this trend: the irradiated sample reaches failure at lower deformation values and at lower levels of mechanical strength.

The decrease in the mechanical performance of the Arboblend V2 Nature material after gamma irradiation can be explained by the physicochemical mechanisms induced by ionizing radiation on the polymer structure and on the lignocellulosic components of the composite. Gamma radiation generates free radicals within the molecular structure of the material. In the case of Arboblend V2 Nature, the results suggest the predominance of molecular chain scission phenomena. The breaking of polymer chains leads to a reduction in molecular weight and, consequently, to a decrease in the mechanical strength and ductility of the material.

In addition, the natural components of the material (cellulose, lignin, and hemicellulose) are sensitive to radiochemical oxidation. Irradiation may generate microcracks at the fiber–matrix interface and may reduce the

adhesion between the composite phases. As a result, stress transfer becomes less efficient, and the material fails more rapidly under mechanical loading.

Based on the experimental results obtained, gamma-irradiated Arboblend V2 Nature cannot be recommended for use in applications involving gamma irradiation.

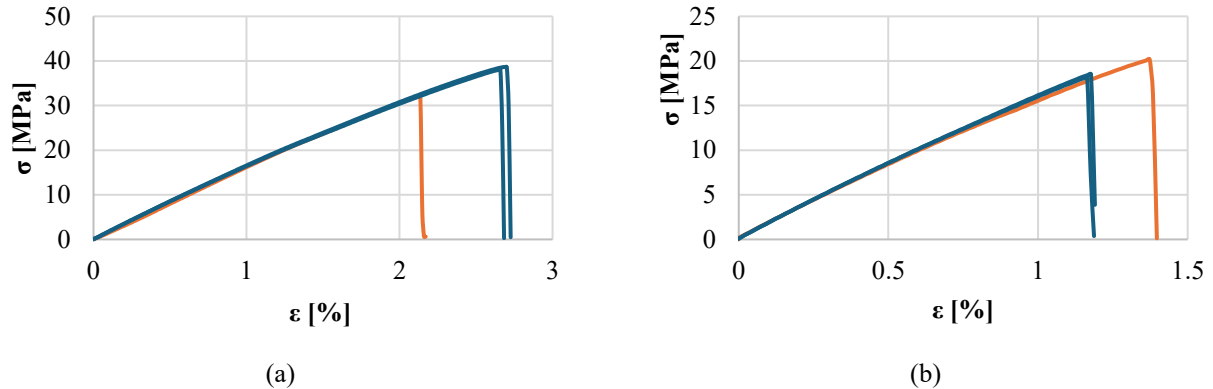


Fig. 1. Strength–elongation graphs, exp. 7: (a) Base Arboblend, (b) Gamma-irradiated Arboblend

### 3.1.2 Comparison between Virgin Arbofill Fichte and Gamma-Irradiated Arbofill Fichte

Table 2 and Figure 2 highlight a different behavior of the Arbofill Fichte material compared to Arboblend V2 Nature following gamma irradiation. In this case, irradiation leads to a moderate improvement in the mechanical properties, particularly in tensile strength and elongation at break.

The experimental values indicate that gamma-irradiated Arbofill Fichte exhibits, in most cases, higher values compared to the virgin material. The tensile strength of the non-irradiated samples is approximately within the range of 25–29 MPa, whereas for the irradiated samples, the values increase to approximately (30–32) MPa.

Analyzing the experimental averages, in Experiment 1, the average tensile strength increases from approximately 26.96 MPa to 31.00 MPa; in Experiment 2, the increase is from 26.58 MPa to 31.71 MPa; and in Experiment 8 (highlighted in Figure 2 and relevant for the graphical comparison), the average strength increases from approximately 29.29 MPa to 31.26 MPa.

This increase corresponds to an improvement of approximately (7–20)%, depending on the experimental conditions.

Table 2. Comparison between Arbofill Fichte and gamma-Irradiated Arbofill Fichte

	Sample	base Arbofill		Irradiated Arbofill	
		Strength (MPa)	Elongation (%)	Sample	Strength (MPa)
Exp 1	1	26.50	4.18	32.37	4.59
	2	27.25	3.90	29.75	3.80
	3	27.12	3.80	30.87	4.24
	<i>Average</i>	26.96±0.40	3.96±0.20	31.00±1.31	4.21±0.40
Exp 2	1	26.50	3.70	32.25	4.80
	2	26.62	3.86	32.25	4.82
	3	26.62	4.27	30.62	4.05
	<i>Average</i>	26.58±0.07	3.94±0.29	31.71±0.94	4.56±0.44
Exp 3	1	25.00	3.96	30.87	3.46
	2	24.62	3.85	27.75	2.57
	3	27.00	4.91	31.37	4.50
	<i>Average</i>	25.54±1.28	4.24±0.58	30.00±1.96	3.51±0.97
Exp 4	1	25.87	4.30	31.25	4.24
	2	26.37	4.23	31.50	3.95
	3	24.62	3.39	31.37	4.06
	<i>Average</i>	25.62±0.90	3.97±0.51	31.37±0.13	4.08±0.15
Exp 5	1	25.62	3.21	30.87	4.08
	2	26.00	4.11	30.35	3.86
	3	26.12	3.22	30.25	4.32

<i>Average</i>		25.91±0.26	3.51±0.52	30.49±0.33	4.09±0.23
Exp 6	1	27.37	3.48	30.50	4.14
	2	28.25	3.35	30.25	3.70
	3	27.37	3.24	29.87	3.75
<i>Average</i>		27.66±0.51	3.36±0.12	30.21±0.32	3.86±0.24
Exp 7	1	27.25	3.52	30.50	4.24
	2	27.25	3.55	30.25	3.79
	3	27.25	3.81	30.00	4.43
<i>Average</i>		27.25±0.00	3.63±0.16	30.25±0.25	4.15±0.33
Exp 8	1	29.12	3.73	30.87	3.95
	2	30.00	3.96	31.00	4.24
	3	28.75	4.39	31.90	5.15
<i>Average</i>		<b>29.29±0.64</b>	<b>4.03±0.34</b>	<b>31.26±0.56</b>	<b>4.45±0.63</b>

The curves shown in Figure 2 confirm that the irradiated samples achieve both higher mechanical strength and slightly greater deformation before failure.

Experiment 8 is particularly significant because it demonstrates the most balanced mechanical behavior. These results suggest an improvement in the structural cohesion and stress transfer within the composite after irradiation.

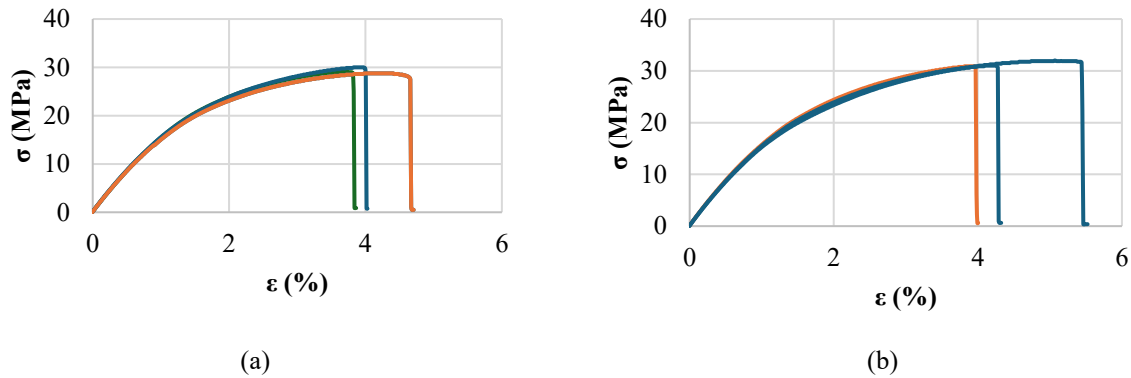


Fig. 2. Strength–elongation graphs, exp. 8: (a) base Arbofill, (b) gamma-irradiated Arbofill

Unlike Arboblend V2 Nature, in the case of Arbofill Fichte, gamma irradiation predominantly promotes the molecular cross-linking process rather than polymer chain scission.

Gamma radiation generates free radicals within the material structure, which lead to the formation of additional intermolecular bonds between the polymer chains. This cross-linking phenomenon results in: increased structural rigidity, improved stress transfer, stabilization of the interface between the matrix and the wood particles/fibers, and reduction of microscopic defects within the material.

The structural components of Arbofill Fichte contributed favorably to the absorption and redistribution of the energy induced by radiation. Under certain dose conditions, the structure of the natural fibers may facilitate mechanical anchoring within the polymer matrix, leading to an increase in tensile strength.

Furthermore, the moderate increase in elongation indicates that the material did not become excessively rigid or brittle after irradiation, suggesting the existence of a favorable balance between cross-linking and molecular degradation.

The obtained results indicate that gamma-irradiated Arbofill Fichte has potential for industrial applications where radiation sterilization, dimensional stability, moderate mechanical strength, and partially biodegradable or bio-based materials are required.

## 3.2 Flexural test

### 3.2.1 Comparison between Virgin Arboblend V2 Nature and Gamma-Irradiated Arboblend V2 Nature

The flexural test results for the Arboblend V2 Nature material clearly indicate a degradation of mechanical properties after gamma irradiation, both in terms of maximum flexural strength and the deformation behavior of the material.

From Table 3, it can be observed that the virgin material exhibits flexural strength values ranging approximately between (9–29) MPa, whereas the gamma-irradiated samples fall within the range of (10–16) MPa. In most

experiments, the average strength of the irradiated material is lower than that of the non-irradiated material, indicating mechanical degradation caused by radiation exposure.

The most significant reductions can be observed in the experiments with initially higher strength values: in Experiment 7, the average strength decreases from approximately 28.78 MPa to 11.05 MPa, corresponding to a reduction of about 61%; in Experiment 6, the decrease is from approximately 27.34 MPa to 11.05 MPa, i.e., nearly 60%; and in Experiment 5, the reduction is also in the range of (58–60) %.

In contrast, for experiments with lower initial values (e.g., Experiment 1), a slight increase in strength after irradiation is observed. However, since this behavior is isolated, it cannot be considered representative of the overall behavior of the irradiated material.

The deformation (elongation) values also indicate a reduction in deformability after irradiation. The irradiated material shows strain values of approximately (0.38–0.57) %, compared to the virgin material, where deformation frequently reaches (1.0–1.2) %. This reduction suggests increased brittleness and decreased toughness under flexural loading.

Table 3. Comparison between Base Arboblend V2 Nature and Gamma-Irradiated Arboblend V2 Nature

	Sample	base Arboblend		irradiated Arboblend	
		Strength (MPa)	Elongation (%)	Sample	Strength (MPa)
Exp 1	1	8.65	0.38	12.98	0.53
	2	7.21	0.31	12.98	0.52
	3	11.53	0.51	11.53	0.50
<i>Average</i>		9.13±2.20	0.40±0.10	12.50±0.84	0.52±0.02
Exp 2	1	18.74	0.79	10.09	0.44
	2	25.95	1.17	10.09	0.43
	3	18.74	0.83	10.09	0.43
<i>Average</i>		21.14±4.16	0.93±0.21	10.09±0.00	0.43±0.01
Exp 3	1	23.07	1.03	12.98	0.51
	2	24.51	1.06	15.86	0.69
	3	24.51	1.05	12.98	0.52
<i>Average</i>		24.03±0.83	1.05±0.02	13.94±1.66	0.57±0.10
Exp 4	1	21.63	0.98	17.30	0.69
	2	24.51	1.03	14.42	0.56
	3	23.07	1.03	14.42	0.56
<i>Average</i>		23.07±1.44	1.01±0.03	15.38±1.66	0.60±0.08
Exp 5	1	27.40	1.15	11.54	0.43
	2	21.63	0.93	12.98	0.49
	3	28.84	1.13	5.76	0.22
<i>Average</i>		25.96±3.82	1.07±0.12	10.09±3.82	0.38±0.14
Exp 6	1	25.78	1.15	11.53	0.46
	2	27.40	1.21	10.09	0.43
	3	28.84	1.23	11.53	0.50
<i>Average</i>		27.34±1.53	1.20±0.04	11.05±0.83	0.46±0.04
Exp 7	1	27.40	1.10	11.53	0.45
	2	28.84	1.15	8.65	0.35
	3	30.11	1.24	12.98	0.51
<i>Average</i>		<b>28.78±1.36</b>	<b>1.16±0.07</b>	<b>11.05±2.20</b>	<b>0.44±0.08</b>
Exp 8	1	24.51	0.97	11.53	0.46
	2	27.40	1.15	13.72	0.57
	3	27.40	1.15	12.98	0.51
<i>Average</i>		26.44±1.67	1.09±0.10	12.74±1.11	0.51±0.06

The decrease in mechanical properties after gamma irradiation can be explained by the molecular degradation of the Arboblend V2 Nature polymer matrix. Gamma radiation causes scission of macromolecular chains and

radiation-induced oxidation, which leads to a reduction in molecular weight and a decrease in the internal cohesion of the material.

Since Arboblend is a biopolymer with natural components, it is more sensitive to radiation-induced degradation processes compared to conventional stabilized engineering polymers.

Based on the obtained results, gamma-irradiated Arboblend V2 Nature is not recommended for industrial applications involving direct radiation exposure.

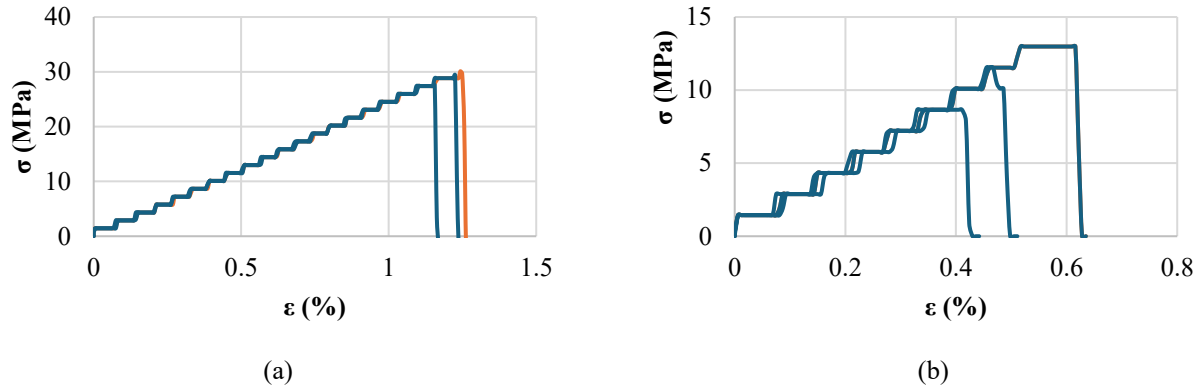


Fig. 3. Strength–elongation graphs, exp. 7: (a) base Arboblend, (b) gamma-irradiated Arboblend

### 3.2.2 Comparison between Virgin Arbofill Fichte and Gamma-Irradiated Arbofill Fichte

The analysis of the flexural test results for the Arbofill Fichte material highlights a different behavior compared to Arboblend V2 Nature, with gamma irradiation in this case leading to a moderate improvement in mechanical properties. Both the flexural strength values and the stability of the mechanical response indicate a positive influence of irradiation on the material structure.

From the experimental data (Table 4), it can be observed that the virgin material exhibits flexural strength values in the approximate range of (23–26) MPa, while the gamma-irradiated samples reach values of approximately (25–27) MPa. The increase is relatively consistent across most experiments, suggesting a favorable structural modification induced by gamma radiation.

The most representative increases are observed in Experiment 3, where the average flexural strength increases from approximately 24.51 MPa to 27.40 MPa, corresponding to an improvement of about (11–12) %; in Experiment 6, where values increase from approximately 24.51 MPa to 26.92 MPa, corresponding to nearly 10%; and in Experiment 5, where the increase is also around (9–10) %.

In Experiment 8, the differences between the virgin and irradiated material are minimal, with nearly similar values, which may indicate that a structural stabilization threshold of the material has been reached.

Regarding specific deformation (elongation), the irradiated material generally exhibits slightly higher values than the virgin material, increasing from approximately (1.7–2.1) % to (2.0–2.5) %. This suggests that the material retains its deformability and does not become brittle after irradiation, unlike the behavior observed in Arboblend V2 Nature.

Table 4. Comparison between Arbofill Fichte and gamma-Irradiated Arbofill Fichte

	Sample	Base Arbofill		Irradiated Arbofill	
		Strength (MPa)	Elongation (%)	Sample	Strength (MPa)
Exp 1	1	23.07	1.86	25.95	2.43
	2	24.51	2.03	25.95	2.58
	3	23.07	1.78	25.95	2.64
	<i>Average</i>	23.55±0.83	1.89±0.13	25.95±0.00	2.55±0.11
Exp 2	1	24.51	2.18	25.95	2.05
	2	24.51	2.02	25.78	2.05
	3	24.51	2.12	25.95	2.10
	<i>Average</i>	24.51±0.00	2.11±0.08	25.89±0.10	2.07±0.03
Exp 3	1	24.51	1.97	27.40	2.20
	2	24.51	2.02	27.40	2.20
	3	24.51	1.99	27.40	2.27

<i>Average</i>		24.51±0.00	1.99±0.03	27.40±0.00	2.22±0.04
Exp 4	1	23.07	1.82	25.95	2.11
	2	24.51	2.19	25.95	1.94
	3	24.51	2.02	27.40	2.19
<i>Average</i>		24.03±0.83	2.01±0.19	26.43±0.84	2.08±0.13
Exp 5	1	23.07	1.69	27.40	2.48
	2	23.07	1.70	25.95	2.10
	3	23.07	1.70	24.52	2.20
<i>Average</i>		23.07±0.00	1.70±0.01	25.96±1.44	2.26±0.20
Exp 6	1	24.51	2.04	27.40	2.50
	2	24.51	2.25	25.95	2.15
	3	24.51	2.07	27.40	2.74
<i>Average</i>		24.51±0.00	2.12±0.11	26.92±0.84	2.46±0.30
Exp 7	1	24.51	1.99	25.95	1.95
	2	24.51	1.89	27.40	2.12
	3	24.51	2.27	27.40	2.21
<i>Average</i>		<b>24.51±0.00</b>	<b>2.05±0.20</b>	<b>26.92±0.84</b>	<b>2.09±0.13</b>
Exp 8	1	25.95	2.11	25.95	2.26
	2	25.95	2.53	25.95	2.27
	3	25.95	2.25	25.95	2.20
<i>Average</i>		25.95±0.00	2.30±0.21	25.95±0.00	2.24±0.04

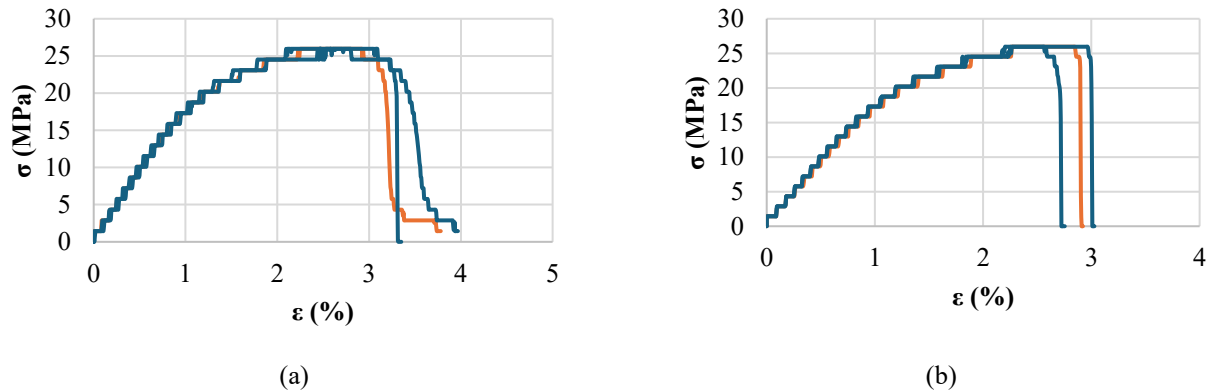


Fig. 4. Strength–elongation graphs, exp. 7: (a) base Arbofill, (b) gamma-irradiated Arbofill

The increase in mechanical properties after gamma irradiation can be explained by the occurrence of cross-linking phenomena within the polymeric structure of the Arbofill Fichte material. Gamma radiation can generate additional bonds between macromolecular chains, leading to: increased structural rigidity, improved load transfers between the components of the composite material, reduced mobility of polymer chains, and enhanced resistance to mechanical loading.

The presence of certain synthetic chemical compounds in the structure of Arbofill contributed to the stabilization of the material after irradiation, favoring cross-linking processes over molecular degradation. This behavior indicates a better compatibility of the material with ionizing radiation exposure compared to Arboblend V2 Nature.

Based on the obtained results, gamma-irradiated Arbofill Fichte can be considered suitable for industrial applications where both moderate mechanical strength and compatibility with sterilization processes or radiation exposure are required. Potential fields of use include: radiation-sterilizable technical packaging; biodegradable components used in the medical industry; lightweight structural elements for equipment occasionally exposed to radiation; technical parts used in laboratories, research facilities, or radiologically controlled environments; and eco-composite components for the automotive or electronics industries where sustainable materials with good mechanical stability are required.

Furthermore, the moderate improvement in strength after irradiation suggests the possibility of using gamma treatment as a method for controlled modification of material properties, aiming to enhance mechanical performance without the addition of extra chemical additives.

In conclusion, the experimental results show that gamma irradiation has a favorable effect on the flexural behavior of Arbofill Fichte, leading to moderate increases in mechanical strength while maintaining good deformability.

#### 4. CONCLUSIONS

The tensile test results show that gamma irradiation significantly influences the mechanical properties of the analyzed biocomposites, with the effects depending on the structure and composition of the material.

In the case of Arboblend V2 Nature, gamma irradiation led to a considerable reduction in tensile strength and elongation at break, indicating degradation of the polymer structure and increased material brittleness. The decrease in mechanical performance is predominantly associated with molecular chain scission and radiation-induced oxidative degradation caused by ionizing radiation.

Arbofill Fichte exhibited a different behavior, with gamma irradiation leading to a moderate increase in tensile strength and the maintenance of a good level of deformability. The improvement in mechanical properties suggests the predominance of molecular cross-linking processes and better compatibility between the polymer matrix and the lignocellulosic phase after irradiation.

Compared to Arboblend V2 Nature, Arbofill Fichte shows higher stability under gamma radiation and greater potential for industrial applications involving sterilization or exposure to gamma ionizing radiation.

The flexural test results highlighted the significant influence of gamma irradiation on the mechanical properties of the analyzed biopolymers, with effects varying depending on material composition.

For Arboblend V2 Nature, gamma irradiation caused a clear degradation of mechanical behavior, reflected in a reduction in flexural strength of approximately (55–60) % in most experiments and a decrease in deformation capacity. This behavior indicates the predominance of polymer chain scission processes and increased brittleness after exposure to ionizing radiation.

In contrast, Arbofill Fichte exhibited a moderate improvement in mechanical properties after irradiation, with flexural strength increases of approximately (8–12) %, while maintaining good deformability. This effect can be attributed to radiation-induced cross-linking phenomena and structural stabilization of the composite material.

Overall, Arbofill Fichte demonstrated superior radiation stability compared to Arboblend V2 Nature, suggesting better compatibility of lignocellulosic composite materials with sterilization processes or radiation-exposed environments.

Based on the obtained results, Arboblend V2 Nature is not recommended for industrial applications involving gamma radiation exposure, whereas Arbofill Fichte may represent a sustainable alternative for technical applications requiring both stable mechanical properties and compatibility with irradiation treatments.

**Author contributions:** CN, IBL: conceptualization (conception or design of the paper); TDM, CDC, MST: data curation (acquisition/analysis/data interpretation); SNM, MC, IBL, TDM: investigation; IBL, CDC: supervision; CN, SNM: initial draft writing, editing, and review. All authors have read and agreed to the published version of the manuscript.

**Funding:** This paper has received no external funding.

**Conflicts of interest:** There is no conflict of interest.

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Received: March 08<sup>th</sup>, 2026 / Accepted: June 15<sup>th</sup>, 2026 / Paper available online: June 20<sup>th</sup>, 2026 © International Journal of Modern Manufacturing Technologies.