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Original article

Study on gamma radiation attenuation and non-ionizing shielding effectiveness of niobium-reinforced novel polymer composite

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ABSTRACT

Advanced radiation applications have been widely used and extended to many fields. As a result of this fact, choosing an appropriate shielding material based on the radiation application has become vital. In this regard, the integration of elements into polymer composites has been investigated and contributed to the quantity and quality of radiation shielding materials. This study reports photon attenuation parameters and electromagnetic shielding effectiveness of a novel polymer composite prepared with a matrix reinforced with three different proportions (5, 10, and 15 wt%) of niobium content. Addition of Nb dopant improves both photon attenuation and electromagnetic shielding effectiveness for the investigated composites. Therefore, Nb(15%) polymer composite with highest concentration has been found to be the best absorber for ionizing and non-ionizing radiations. Consequently, the performed analyzes provide evidences that the prepared Nb-reinforced polymer composite could be effectively used as photon radiation attenuator and electromagnetic shielding material.

1. Introduction

Radiation and radiation related terms are often encountered in various parts of life since different types of radiation are widely used and employed in high-performance/technology applications such as particle accelerators, nuclear reactors, research centers, medical industry, agricultural usages, aerospace applications, etc. One of the main components in these advanced applications is radiation shielding since undesired exposure can introduce radiative damage to involved staff, its environment, and a human being [1–3]. Here, it is a well-known fact that the possible harm of radiation exposure depends on the exposure time, absorbed dose, type, and energy of associated radiation. Among the radiation types, high energetic photons (X- and gamma rays) are emitted by an electron or created by nuclear decay and called as ionizing radiation, which is the most penetrating electromagnetic radiation. There is also a non-ionizing radiation category, which is also classified under the electromagnetic spectrum. The definition difference between ionizing and non-ionizing radiation is that ionizing radiation carries adequate energy to take tightly bound electrons out from the orbital of the atom while non-ionizing radiation cannot remove electrons but can vibrate atoms [4]. Both could cause particular and harmful health issues, and more details on the health effects of these radiation types could be found in Refs. [1–4].

Based on the literature, it could be safely stated that some polymer composites are flexible and durable materials and could be easily reinforced with different elements. With these properties, they are good candidates to attenuate radiation and could be useful in the production of radiation protection materials. In this regard, photon attenuation efficiencies for ionizing radiation and

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electromagnetic shielding effectiveness (EMSE) for non-ionizing radiation of different polymer composites have been separately reported to prevent the potential hazards of varying radiation types mentioned above. In this concept, Viskadourakis et al. [5] investigated EMSE of various 3D printed polymeric composite structures in the electromagnetic spectrum of 3.5–7 GHz, and highlighted good effectiveness of the considered composites on electromagnetic shielding. In addition, Xia et al. [6] fabricated hybrid composites made of epoxy resin, aluminum sheets, and natural fiber mats. They found that the prepared composites exhibited excellent electromagnetic shielding performance in the electromagnetic spectrum of 8–12 GHz. In another study, Chou et al. [7] mixed nickel in the polymer melt in order to increase the interaction of electromagnetic radiation with the polymer, and obtained better electromagnetic shielding effectiveness with additive material into to polymer matrix. More electromagnetic shielding effectiveness studies for the non-ionizing category [8–12] could be listed.

Therewithal, there are also many ionizing radiation attenuation studies using polymer matrixes. For example, Özkalaycı et al. [13] investigated gamma radiation shielding properties of $PbCl_2$ doped polymer composite samples in a gamma radiation energy range of 59.5–1408.0 keV. They found that the radiation protection efficiency was enhanced with a considered dopant, and this improvement increased with the increase of $PbCl_2$ amount in the prepared polymer composite. In addition to gamma attenuation experiments, Harrison et al. [14] fabricated polyethylene/boron nitride composites and evaluated the prepared samples for mechanical and neutron shielding properties. In another study, Cherkashina et al. [15] set up the experimental design to assess the protective properties of polyimide composite with bismuth silicate against gamma-ray energy (0.4 MeV and 0.662 MeV) and electron energy (from 1 to 6 MeV). Besides, Kaçal et al. [16] evaluated experimentally and theoretically the gamma radiation attenuation properties of various polymers with the help of HPGe detector and XCOM computer program, where the gamma energy is ranging from 81 to 1333 keV. All listed studies above reported significant improvement of radiation shielding for the considered materials, and much more radiation shielding study could be further read in Refs. [17–24]. In short, the experimental and theoretical studies performed up to now have revealed good evidences that polymer composites reinforced with element/compound truly deserve to be investigated in order to have promising radiation attenuator and electromagnetic shielding material.

In this study, both photon shielding properties and electromagnetic shielding effectiveness were taken into account for a novel polymer composite doped with niobium element, and to the best of the author's knowledge, it is the first time that both parameters have considered together in one presented work. Nuclear radiation attenuation parameters of the prepared composite were measured as a function of photon energy, which is ranging from 59.5 to 1408.0 keV. The mass attenuation coefficients were compared and validated with that of XCOM theoretical expectations. The EMSE tests of the polymer composite were conducted with the Keysight P281B waveguide between 12.4 and 18.0 GHz (Ku-Band) frequency ranges. The obtained outcomes are quite useful in determining the optimum shield parameters and designing an alternative/innovative shielding material for various radiation and related applications.

2. Materials and methods

2.1. Sample preparation

The prepared samples were used in ionizing and non-ionizing shielding tests. The considered composites consist of unsaturated polyester (base resin), cobalt octoate (accelerator), methyl ethyl ketone peroxide (initiator), and Niobium (dopant). In order to have a complete and proper assessment of the dopant amount impact on radiation protection, the composites are prepared with three different proportions of niobium (Nb). The considered proportions were listed as 5, 10, and 15%. The prepared samples have 1 cm radius and 1 cm thickness. Elemental weight fractions were determined with the help of the WinXCOM [25] program and exact percentages of elements were given in Table 1.

2.2. Sample analysis

In this work, as motivated earlier, two different analyses were performed: ionizing and non-ionizing photon shielding tests of the prepared samples. Ionizing radiation shielding tests were carried out with help of a basic High Purity Germanium (HPGe) detector based measurement system at lab frame as a function of photon energy at 22 different values, which varies from 59.5 to 1408.0 keV. The upper picture of Fig. 1 illustrates the ionizing photon shielding experimental setup. Each measurement was repeated three times in order to obtain statistical uncertainties. The obtained experimental values were further validated using WinXCOM [25] computer program that provides theoretical photon attenuation coefficients.

For the non-ionizing photon shielding test, the Keysight P281B waveguide and the Agilent the PNA-L model network analyzer were used to measure scattering parameters (S11/S22 and S12/S21) of samples, and the lower picture of Fig. 1 shows the measurement setup. The measurement system was calibrated before the test with the keysight (Agilent) 85056A calibration kit. As mentioned earlier, the non-ionizing photon shielding experiments were conducted in the electromagnetic spectrum of 12.4–18 GHz.

2.3. Analysis methodology

As can be seen from the experimental design of the ionizing photon shielding test (upper picture of Fig. 1), the prepared samples are placed between HPGe detector and the considered radioactive source. The collimators between the sample and radioactive source help adjusting the beam shape. The detector is used to measure transmitted gamma radiation (I) (with sample) and incident (I_0) (without the sample) intensities of each point source. In order to determine the linear (μ) and mass (μ/ρ) attenuation coefficients, the measured intensity peaks were taken into the calculations, where μ and ρ terms are used to define the reduction of radiation intensity emitted from the point source passing through a target material and the density of the considered sample. The mathematical statement of the linear attenuation coefficient is given by Eq. (1):

$$\mu = -\frac{ln\frac{I}{I_0}}{x} \tag{1}$$

where x stands for the thickness of Nb-reinforced novel polymer composite in unit of cm so that the unit of μ is given as cm^{-1}. After obtaining linear attenuation coefficient, the mass attenuation coefficient values of composites were determined using the mass density of composites. The theoretical mass attenuation values could be further calculated using a well-known mixture rule ($(\mu/\rho)_{comp.} = \sum W_i(\mu/\rho)_i$) for each prepared composite. In addition to the coefficients, other considered radiation attenuation parameters are mean free path (MFP), tenth value layer (TVL), half value layer (HVL), effective electron density(N_E), effective atomic number(Z_{eff}) and radiation protection efficiency (RPE). MFP ($1/\mu$), TVL ($ln10/\mu$), and HVL ($ln2/\mu$) are the terms to define the necessary

Table 1
Elemental abundance and weight fractions for polymer composites reinforced with Nb.

Sample	Percent Elemental Abundance					ρ (g/cm^3)	Weight Fractions				
	H	C	O	Co	Nb		H	C	O	Co	Nb
Nb(5%)	4.4475	56.9947	34.0057	0.0271	4.5249	1.3470	0.04448	0.56992	0.34004	0.00027	0.04528
Nb(10%)	4.2550	54.5274	32.5336	0.0260	8.6580	1.3568	0.04254	0.54547	0.32526	0.00026	0.08647
Nb(15%)	4.0785	52.2649	31.1837	0.0249	12.4481	1.3678	0.04079	0.52267	0.31185	0.00025	0.12444

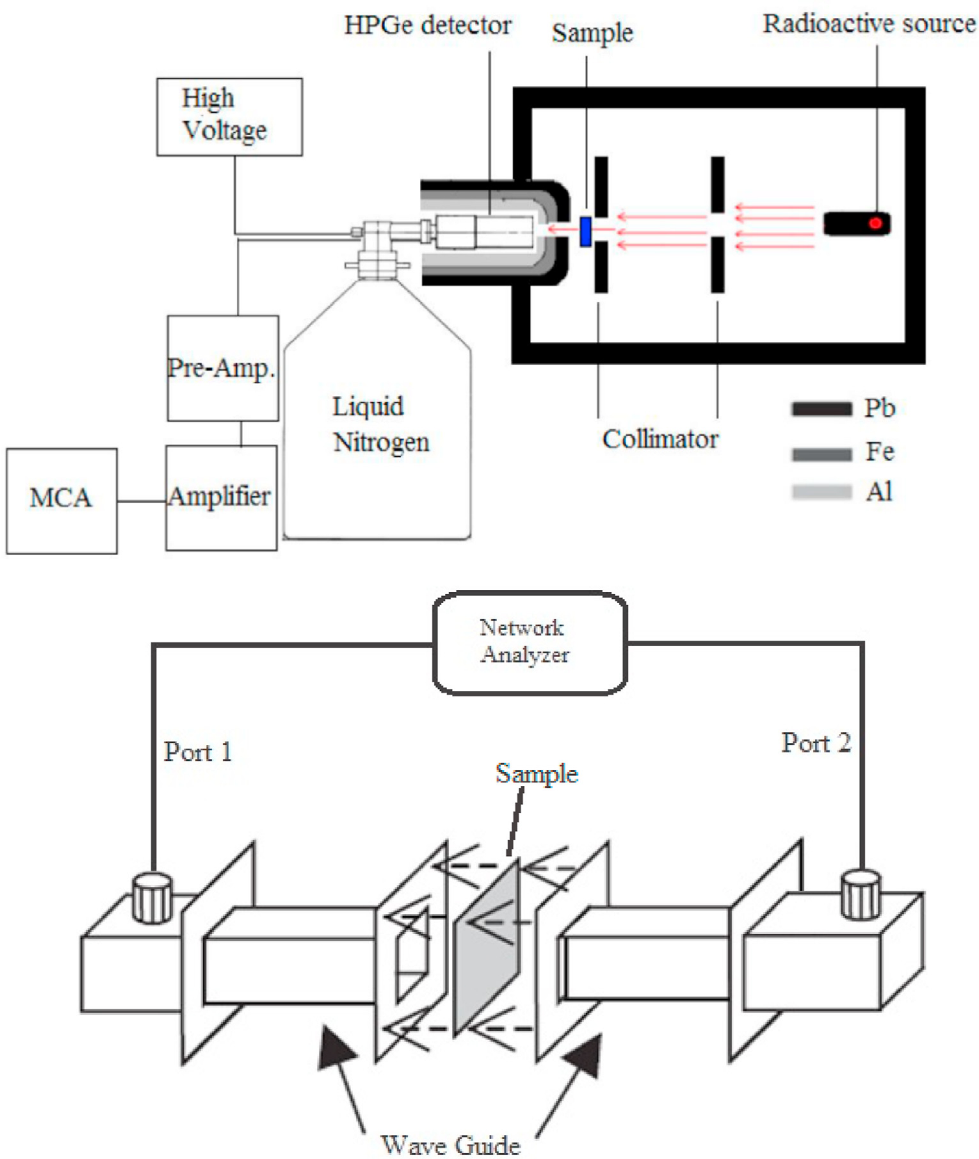

Fig. 1. The experimental setups for gamma radiation (upper) and electromagnetic (lower) shielding measurements.

sample thickness for transmission of the initial radiation intensity to 36.8%, 10% and 50%, respectively. The mathematical statements of the remaining radiation attenuation parameters are given by Equations (2)–(4) [26].

$$N_E = N_A \frac{Z_{eff}}{<A>} \tag{2}$$

$$Z_{eff} = \frac{\sum_i f_i A_i \left(\frac{\mu}{\rho}\right)_i}{\sum_j f_j \frac{A_j}{Z_j} \left(\frac{\mu}{\rho}\right)_j} \tag{3}$$

$$RPE = \left(1 - \frac{I}{I_0}\right) 100 \tag{4}$$

where N_A, <A>, f_i, A_i and Z_j stand for Avogadro number, the average atomic mass, the molar fraction of the elements, the atomic weight and atomic number, respectively.

Right after the calibration of measurement system for non-ionizing tests, the test was performed without using a sample, and the obtained results were recorded. Then, the test was repeated with the prepared Nb-reinforced novel polymer composite samples. EMSE is the logarithmic form of the ratios between the electric field (E), magnetic field (H), or power (P) intensity results obtained from measurements with (E_T) and without (E_0) shielding material. EMSE values were calculated as dB according to Eq. (5) [27].

$$EMSE = 20\log\left|\frac{E_0}{E_T}\right| = 20\log\left|\frac{H_0}{H_T}\right| = 10\log\left|\frac{P_0}{P_T}\right| \quad (5)$$

On the other hand, according to the Schelkunoff decomposition, total shielding effectiveness is the sum of the absorption, reflection, and multiple internal reflection shielding components [28]. In previous studies, it was noted that both absorption and reflection supports EMSE properties, and the increase of the reflection component may cause secondary interference pollution from the shield to the environment [29]. Besides, the absorption capability of shield material is effective on the visibility in radar [30]. Current studies suggest that EMSE, absorption, and reflection properties of the shield should be evaluated separately for comprehensive electromagnetic characterization. Transmitted (T), reflected (R), and absorbed (A) power values can be calculated with Equations (6)–(8) [31,32].

$$T = \left|\frac{\textit{Transmitted electric field}}{\textit{Incident electric field}}\right|^2 = \left|\frac{E_T}{E_i}\right|^2 = |S_{12}|^2 = |S_{21}|^2 \quad (6)$$

$$R = \left|\frac{\textit{Reflected electric field}}{\textit{Incident electric field}}\right|^2 = \left|\frac{E_R}{E_i}\right|^2 = |S_{11}|^2 = |S_{22}|^2 \quad (7)$$

$$A = 1 - (T + R) \quad (8)$$

EMSE, T, R, and A data were analyzed statistically. Here, the values of EMSE, R, and A values were chosen as the dependent variable, while the concentration of niobium (Nb) was selected as the independent variable. The normality of distribution was determined with the Kolmogorov–Smirnov test, and R/A power ratios and EMSE of samples were compared with Kruskal–Wallis, and Mann–Whitney U non-parametric tests.

3. Results and discussion

The strategy of the presented work depends on ionizing and non-ionizing radiation tests. As described in Section 2, Nb-reinforced novel polymer composites were prepared with elemental weight fractions presented in Table 1. Their density values of Nb(5%) and Nb(15%) jump to 1.3470 and 1.3678 g/cm^3 by increasing the undoped composite density as much as 13.10% and 14.84%, respectively. The density of undoped composite sample was given as 1.1910 g/cm^3 in our previous study [13]. Then, the linear and mass attenuation coefficients at different Nb concentrations were obtained and calculated for a wide energy range of 59.5–1408.0 keV, which are shown on upper and lower rows of Fig. 2, respectively. Both linear and mass attenuation curves indicate an exponential decrease with photon energy increase. The figure also shows the enhancements on the coefficients with increase of Nb dopant amount, which are clearly seen from left histogram to right one. The enhancements are obvious at low photon energy values while the coefficients are almost the same at higher energy region. The same trend has been observed for other samples such as granite [33], concrete [34] and alloys [35] and greener products [36].

Moreover, WinXCOM software is utilized to compare with those of the experimental results at the various energies of 59.5–1408.0 keV. The theoretical μ/ρ results are calculated taking into account the elemental compositions of the samples under investigation. The relative deviation (RD) between mass attenuation coefficients with help of experimental and WinXCOM computer program can be estimated by using the following equation [37]:

$$RD\ (\%) = \left|\left(\frac{\frac{\mu}{\rho_{exp}} - \frac{\mu}{\rho_{XCOM}}}{\frac{\mu}{\rho_{exp}}}\right)\right| * 100 \quad (9)$$

Fig. 2 and Table 2 also provide a well comparison of experimental values with theoretical expectations. The maximum discrepancy between theoretical and experimental evaluations is found to be at about 5%. This is an indication of solid experimental setup, so that this test design could be safely used to assess the attenuation characteristics of the prepared polymer composites.

In order to discuss whether a material is sufficient to block/absorb energetic gamma radiation, MFP, TVL and HVL values should also take into consideration. In this regard, Fig. 3 presents graphical illustration of these parameters as a function of gamma energy since it is the argument of μ. It is clearly seen that these three parameters behave similar and significantly increase with the energy increase. Once the obtained MFP, TVL and HVL distributions of the prepared samples at different Nb proportions are evaluated, it could be safely stated that the materials show almost identical results with each other after about 300 keV energy level. In the region of 60–300 keV, the best attenuation property is exhibited by the sample with Nb(15%). For the complete evaluation, it could be stated that the MFP, TVL and HVL values herewith were decreases in order as Nb(5%) with 6.397 cm > Nb(10%) with 6.373 cm > Nb(15%) with 6.234 cm at 661.7 keV. The density dependence of MFP, TVL and HVL values in this study has been found for previous published materials such as polymer based composites [21], glasses [38] and ceramics [39]. As a result, it can be said that increasing the Nb concentration leads to an rise in the density of the fabricated polyester composites and improvisation of the photon shielding characteristics for the investigated absorber.

The next two parameters for ionizing photon tests taken into account in the presented work are Z_{eff} and N_E. These parameters are also a well indicator of radiation attenuation materials, and both are related to each other [40]. Figs. 4 and 5 show the measured effective atomic numbers and the effective electron densities of the prepared novel polymer composites at different Nb concentrations in 3D graphs, respectively. The values of Nb(5%), Nb(10%) and Nb(15%) samples for the present parameters are in the range 8.3492–4.5869, 11.4018–4.7479 and 13.9437–4.9075 for Z_{eff}, and for 6.8512×10^{26}–3.7639×10^{26}, 9.3721×10^{26}–3.9027×10^{26} and 11.5177×10^{26}–4.0537×10^{26} electrons/g for N_E, respectively. Obviously, the dopant amount strongly affects the parameters of N_E and Z_{eff} since remarkable differences between Nb(5%) and Nb(15%) were observed, where the N_E value of Nb(15%) is about 1.5 times greater than the N_E value of Nb(5%) up to 300 keV gamma energy region. This difference decreases sharply above 300 keV, and Nb(15%) is about %8 bigger than the one observed for Nb(5%). Similar discussions are also valid for the Z_{eff} results. Both of the parameters could be ranked in order of Nb(5%) < Nb(10%) < Nb(15%).

Last but not least ionizing photon shielding test parameter is the RPE, which is also calculated as a function of the gamma energy. As shown in Fig. 6, the RPE of the prepared composites decreases with increase of the energy. Interestingly, it is ranked in order of

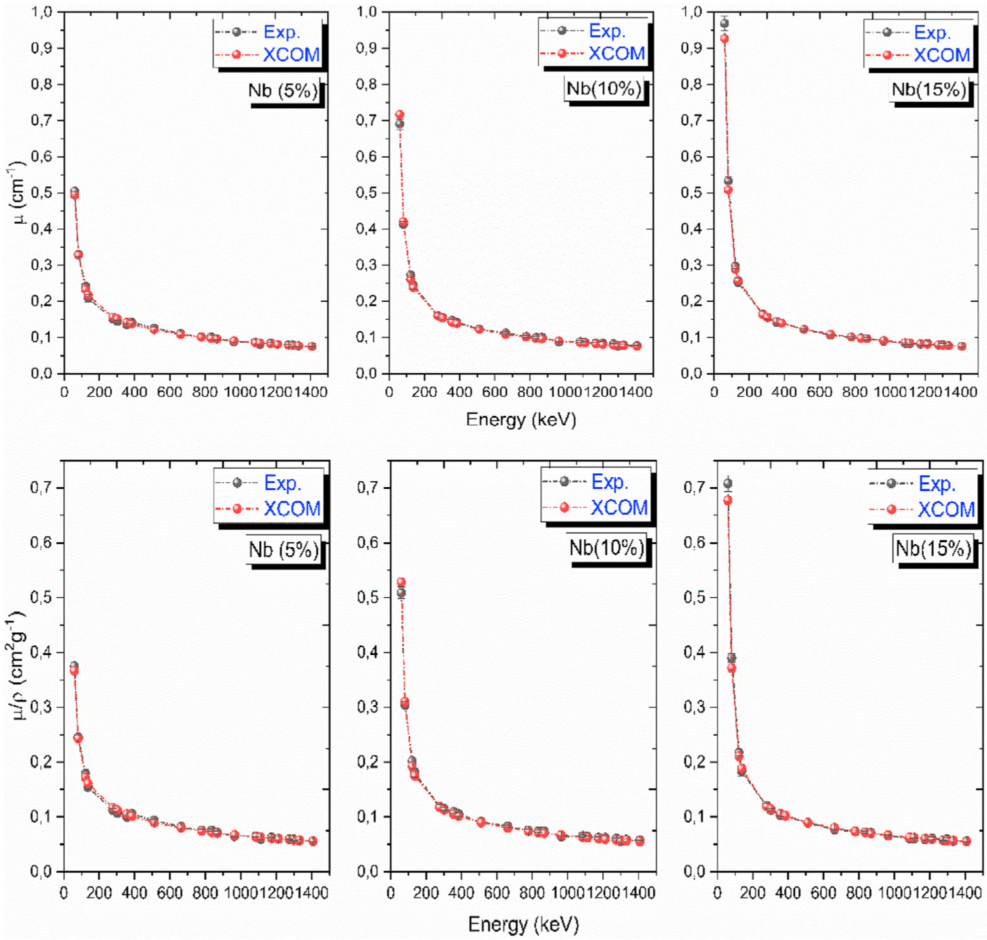

Fig. 2. The linear (upper) and mass (lower) attenuation coefficients at different Nb concentrations.

Table 2
Linear attenuation coefficient and radiation protection efficiency results for polymer composites reinforced with Nb.

Energy (keV)	Nb(5%)			Nb(10%)			Nb(15%)		
	μ (cm^{-1})		RPE (%)	μ (cm^{-1})		RPE (%)	μ (cm^{-1})		RPE (%)
	Experimental	XCOM	Experimental	Experimental	XCOM	Experimental	Experimental	XCOM	Experimental
59.5	0.5052 ± 0.0104	0.4939	43.58 ± 0.21	0.6906 ± 0.0143	0.7170	52.83 ± 0.28	0.9687 ± 0.0202	0.9270	62.37 ± 0.37
81.0	0.3303 ± 0.0068	0.3277	31.22 ± 0.14	0.4127 ± 0.0085	0.4207	36.17 ± 0.17	0.5336 ± 0.0112	0.5084	41.63 ± 0.27
122.1	0.2422 ± 0.0053	0.2321	24.00 ± 0.22	0.2734 ± 0.0060	0.2610	25.73 ± 0.24	0.2973 ± 0.0067	0.2883	25.92 ± 0.27
136.5	0.2084 ± 0.0108	0.2171	21.03 ± 1.01	0.2451 ± 0.0112	0.2381	23.41 ± 0.97	0.2517 ± 0.0125	0.2581	22.43 ± 1.02
276.4	0.1511 ± 0.0049	0.1570	15.74 ± 0.41	0.1609 ± 0.0053	0.1601	16.06 ± 0.42	0.1650 ± 0.0058	0.1631	15.34 ± 0.44
302.9	0.1439 ± 0.0035	0.1512	15.04 ± 0.20	0.1552 ± 0.0038	0.1536	15.54 ± 0.23	0.1548 ± 0.0037	0.1561	14.46 ± 0.20
356.0	0.1351 ± 0.0028	0.1415	14.19 ± 0.08	0.1480 ± 0.0031	0.1431	14.87 ± 0.08	0.1414 ± 0.0029	0.1448	13.30 ± 0.08
383.9	0.1422 ± 0.0044	0.1371	14.88 ± 0.35	0.1423 ± 0.0048	0.1385	14.34 ± 0.39	0.1399 ± 0.0047	0.1399	13.16 ± 0.36
511.0	0.1261 ± 0.0026	0.1215	13.32 ± 0.06	0.1236 ± 0.0025	0.1222	12.58 ± 0.06	0.1222 ± 0.0025	0.1230	11.60 ± 0.06
661.7	0.1110 ± 0.0023	0.1084	11.82 ± 0.06	0.1127 ± 0.0023	0.1088	11.54 ± 0.05	0.1058 ± 0.0022	0.1093	10.13 ± 0.05
778.9	0.1020 ± 0.0027	0.1005	10.91 ± 0.19	0.1029 ± 0.0027	0.1008	10.59 ± 0.18	0.1009 ± 0.0026	0.1013	9.68 ± 0.16
834.8	0.1021 ± 0.0025	0.0973	10.92 ± 0.16	0.1007 ± 0.0026	0.0976	10.38 ± 0.17	0.0988 ± 0.0025	0.0980	9.49 ± 0.15
867.4	0.0965 ± 0.0033	0.0955	10.36 ± 0.29	0.1006 ± 0.0035	0.0958	10.37 ± 0.30	0.0972 ± 0.0038	0.0962	9.34 ± 0.31
964.1	0.0878 ± 0.0019	0.0908	9.47 ± 0.09	0.0874 ± 0.0019	0.0910	9.07 ± 0.09	0.0898 ± 0.0020	0.0913	8.66 ± 0.08
1085.9	0.0875 ± 0.0022	0.0856	9.44 ± 0.15	0.0887 ± 0.0023	0.0858	9.20 ± 0.15	0.0833 ± 0.0021	0.0861	8.06 ± 0.13
1112.1	0.0806 ± 0.0017	0.0846	8.73 ± 0.07	0.0869 ± 0.0019	0.0848	9.02 ± 0.07	0.0832 ± 0.0018	0.0851	8.05 ± 0.06
1173.2	0.0847 ± 0.0018	0.0824	9.15 ± 0.06	0.0842 ± 0.0018	0.0825	8.75 ± 0.06	0.0813 ± 0.0017	0.0828	7.88 ± 0.05
1212.9	0.0812 ± 0.0038	0.0810	8.79 ± 0.37	0.0843 ± 0.0041	0.0811	8.76 ± 0.38	0.0834 ± 0.0039	0.0814	8.07 ± 0.34
1274.5	0.0798 ± 0.0017	0.0789	8.64 ± 0.05	0.0826 ± 0.0017	0.0791	8.59 ± 0.05	0.0788 ± 0.0016	0.0793	7.65 ± 0.04
1299.1	0.0794 ± 0.0030	0.0782	8.60 ± 0.28	0.0756 ± 0.0028	0.0783	7.89 ± 0.25	0.0812 ± 0.0029	0.0786	7.87 ± 0.23
1332.5	0.0763 ± 0.0016	0.0771	8.28 ± 0.05	0.0793 ± 0.0017	0.0773	8.26 ± 0.05	0.0773 ± 0.0016	0.0775	7.51 ± 0.04
1408.0	0.0756 ± 0.0016	0.0750	8.21 ± 0.04	0.0776 ± 0.0016	0.0751	8.10 ± 0.04	0.0765 ± 0.0016	0.0754	7.43 ± 0.03

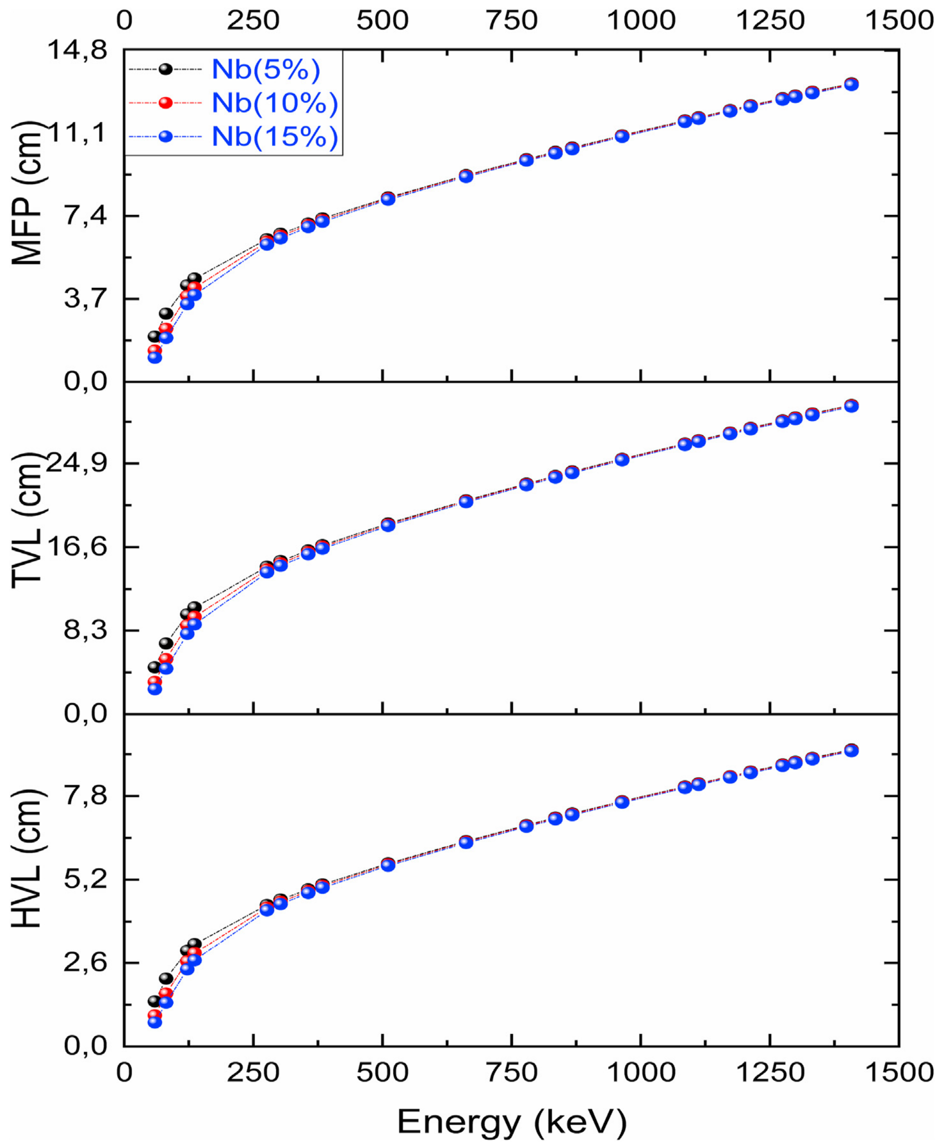

Fig. 3. The obtained MFP, TVL, HVL distributions of the polymer composite prepared with a matrix reinforced with different proportions of niobium.

Nb(5%) < Nb(10%) < Nb(15%) for the first four energy points while after 383.9 keV, the order switches to Nb(15%) with 7.51% < Nb(10%) with 8.26% < Nb(5%) with 8.28%, i.e., at 1332.5 keV. The reason for this is undoubtedly that the prepared composites have low atomic number elements and the Compton scattering cross section is dominant at these energies. The numerical values of the linear attenuation coefficients and radiation protection efficiencies of the prepared composites could be found in Table 2.

As a result of non-ionizing photon shielding tests, EMSE, reflected, and absorbed power ratios of composites having different Nb concentrations (5, 10, and 15%) are given in Fig. 7. The Kolmogorov–Smirnov test showed that the distribution of measurement data was not normal ($p < 0.05$), and Kruskal–Wallis, and Mann–Whitney U non-parametric test results are provided by Table 3. Statistical analyzes showed that the increase in Nb concentration increased the EMSE of samples, and the EMSE of samples reached up to 13.5 dB values. Similarly, the absorbed power ratio by the samples was higher for higher Nb densities. The possible reason for these results is the increase in the number of waves that make secondary reflections and turn into heat due to the increasing Nb concentration. Electromagnetic shielding is provided by the metal content in the composite structure. Polyester that is the other component of the composite structure is transparent in the electromagnetic field due to its electrical insulating properties [41]. Previous studies noted that the increasing amount of metal component increases the EMSE due to the increase in the thickness of the conductive layer and decrease of the gaps in the structure [31,32,42,43].

4. Conclusions

In short, this study reports the combination of two tests for radiation protection by conducting two experimental setup: ionizing and non-ionizing photon shielding measurements. Photon attenuation parameters for ionizing part and electromagnetic shielding effectiveness for non-ionizing section were determined for the polymer composites prepared with a matrix reinforced with three different proportions (5, 10 and 15 wt%) of Nb. The obtained radiation protection efficiencies of the polymer composites at different Nb concentration were compared, and a strong evidence

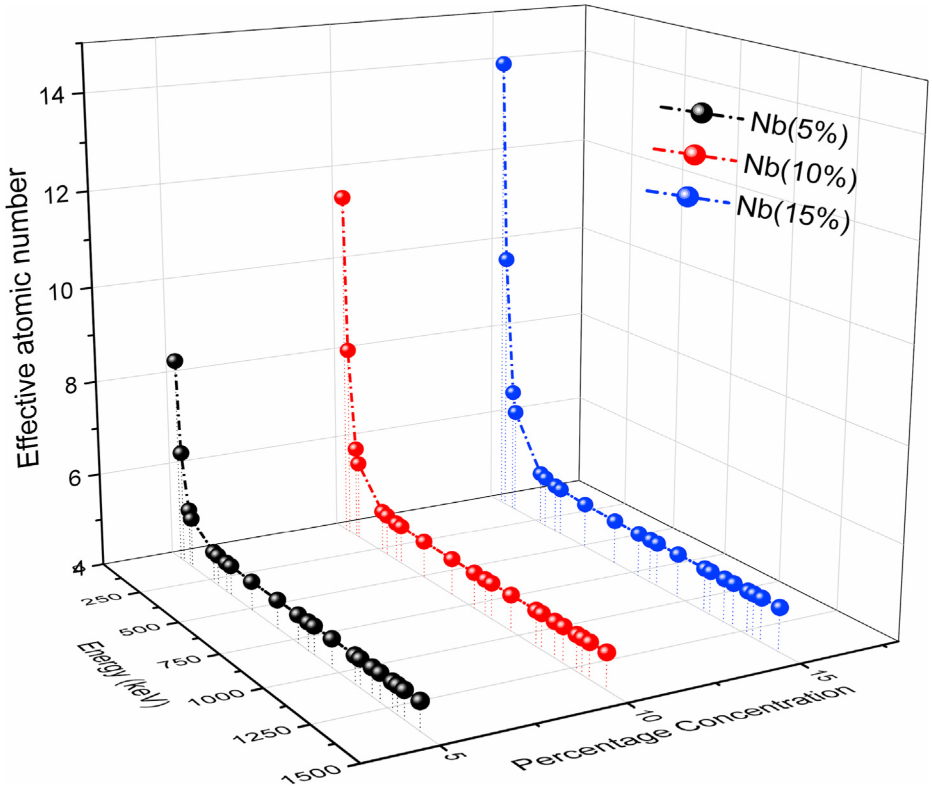

Fig. 4. The effective atomic numbers of the prepared polymer composites at different Nb concentrations.

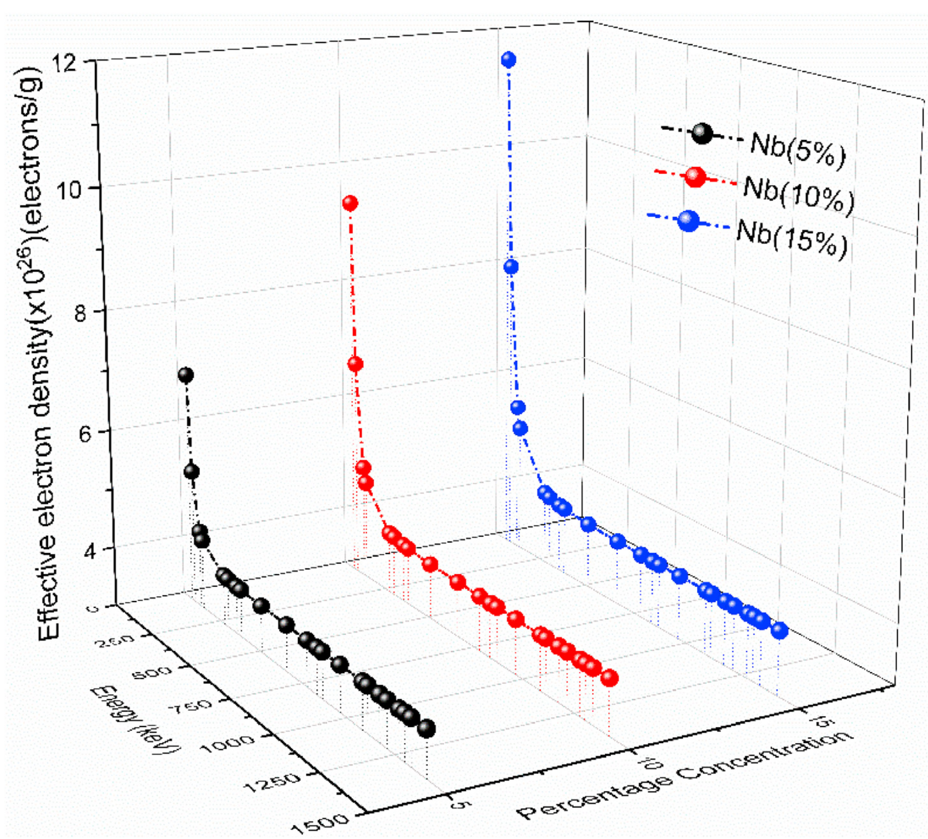

Fig. 5. The effective electron densities of the prepared polymer composites at different Nb concentrations.

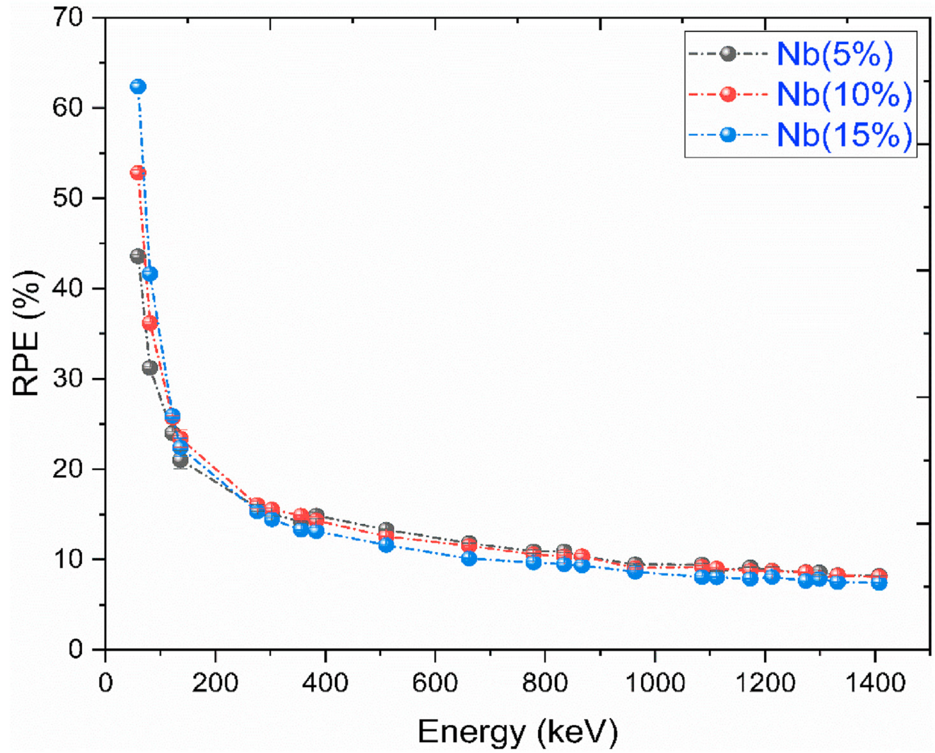

Fig. 6. The obtained radiation protection efficiencies of the prepared polymer composites at different Nb concentrations.

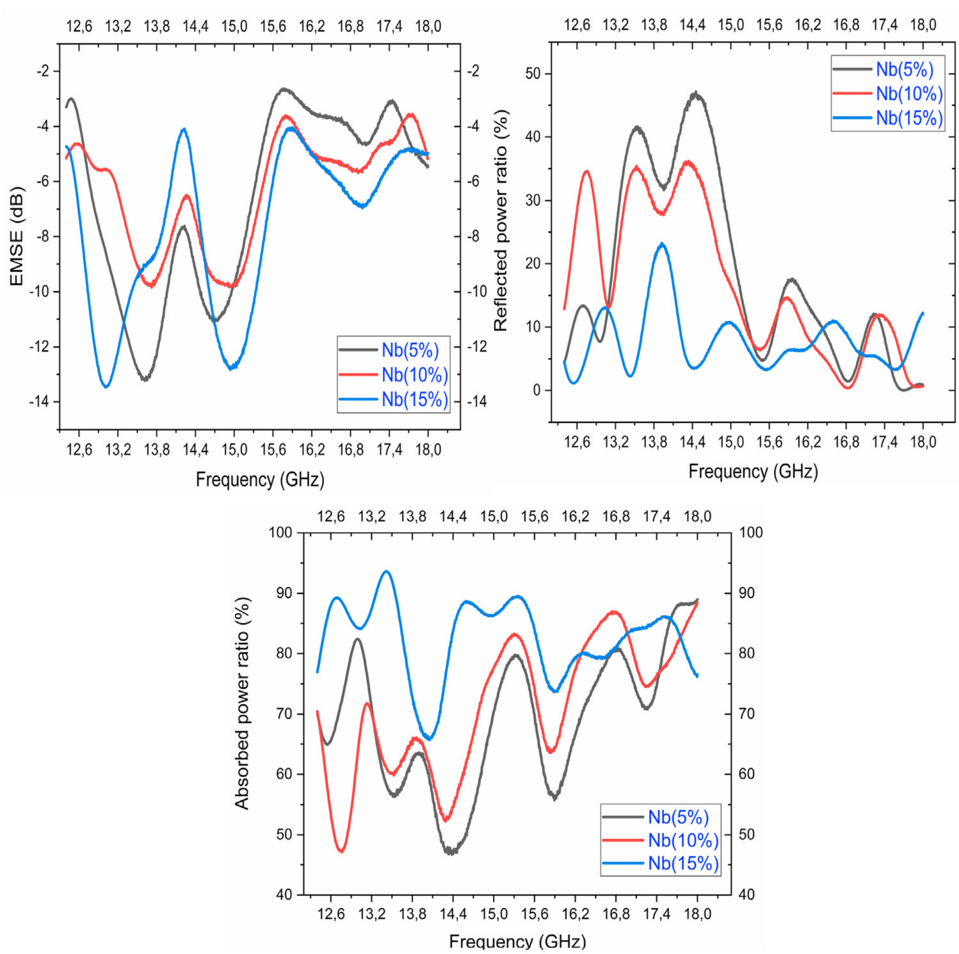

Fig. 7. EMSE, reflected and absorbed power ratios of composites with different Nb concentrations.

Table 3
*Kruskal-Wallis and [a]Mann-Whitney U tests statistics for different Nb concentration.

	Nb Concentration	EMSE	Absorbed power ratio	Reflected power ratio
Mean Ranks	*5%*	1333.73	1086.61	1732.45[a]
	10%	1403.63	1242.49	1718.39[a]
	15%	1768.64	2176.90	1055.16
Asymp. Sig.		0.000*	0.000*	0.000*

There is a significant difference among the samples.
[a] The difference between the samples is not significant.

was found that doping polymer composite with more Nb element significantly increases the materials' photon radiation protection ability in low energy region. Hence, Nb polymer composite with highest amount of 15% has been found to be the most superior absorber among the fabricated composites for ionizing and non-ionizing radiations, for example, Nb(15%) with a lowest MFP and TVL values of 12.898 and 29.708 cm at 1332.5 keV, respectively. This statement could be expressed at least for the considered proportions. In this section, the accuracy of experimental setup was validated with theoretical results obtained using WinXCOM computer program, and negligible discrepancies (below 5%) were found.

On the second part of the analysis, the Agilent the PNA-L model network analyzer was utilized to obtain EMSE, reflected and absorbed power ratios of composites with different Nb densities. Here, the experiments were conducted in the electromagnetic spectrum of 12.4–18.0 GHz. The performed analyzes showed that the increase in Nb concentration increased the EMSE and absorbed power ratio of samples, and the EMSE of samples reached up to 13.5 dB values, which could be due to the fact that the increasing Nb concentration in the composite material possibly increase the number of waves that make secondary reflections. This provides a valid discussion on that promising electromagnetic shielding could be obtained using the considered the metal content in the composite structure.

As a recommendation, the correlations among mechanical, structural, radiation shielding parameters and so on can be studied in detailed through a reliable mathematical model to determine the optimum amount of Nb filler materials in the polymer composite for designing a unique shield which utilizes in different practices such as radiation oncology, nuclear plants and research laboratories.

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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