SHIELDING PROPERTIES AND RADIATION MODIFICATION OF MAGNETIC NANOPARTICLE-FUNCTIONALIZED TEXTILES

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ABSTRACT

This study contributes to the development of multifunctional shielding textiles effective against both electromagnetic interference (EMI) and ionizing radiation. Wool-blend fabrics were modified with Fe_3O_4 magnetic nanoparticles to create flexible composites with strong frequency-dependent absorption and reflection of electromagnetic fields, along with protection against alpha and beta particles. Magnetic susceptibility analysis revealed that, in some cases, radiation exposure unexpectedly enhanced the material's magnetic properties, suggesting beneficial structural changes in the nanoparticles. These findings open new possibilities for adaptive "smart" textiles that not only withstand radiation but may improve under it—paving the way for use in wearable electronics, aerospace, and next-generation protective clothing.

Keywords: *magnetic shielding, radiation protection, magnetic textiles, Fe_3O_4 nanoparticles, shielding effectiveness, electromagnetic absorption*

1. INTRODUCTION

Electromagnetic and nuclear radiation pollution pose significant risks to both human health and technological systems. The increasing exposure to ionizing and non-ionizing radiation necessitates the development of advanced shielding materials to mitigate these threats [1]. Traditional shielding methods, including lead-based materials and metal coatings, provide effective radiation protection; however, they present several drawbacks, such as high density, toxicity, and limited flexibility. As a result, alternative materials, particularly textiles embedded with functional nanomaterials, have gained attention due to their lightweight nature, adaptability, and improved protective capabilities [2, 3].

Among various nanomaterials, magnetic nanoparticles, particularly iron oxides (magnetite (Fe_3O_4) and maghemite (gama-Fe_2O_3)), have demonstrated significant potential in radiation shielding applications. These nanoparticles exhibit unique magnetic properties, such as high saturation magnetization and frequency-dependent absorption of electromagnetic waves, which make them suitable for mitigating electromagnetic interference (EMI) [4–6]. Furthermore, textile-based composites modified with magnetic nanoparticles offer a flexible and adaptable shielding solution, making them ideal for wearable radiation protection [7–9], or electronic component shielding.

The integration of magnetic nanomaterials into textiles has led to notable advancements in radiation shielding. Studies have shown that Fe_3O_4-coated textiles effectively attenuate both ionizing radiation, such as alpha and beta particles, and non-ionizing electromagnetic radiation [10]. Compared to conventional metal-based shielding materials, magnetic textiles provide a balance between protection, weight reduction, and breathability, making them more practical for various applications, including healthcare, aerospace, and military defense [11]. Despite these advantages, several challenges remain in the development of radiation-shielding textiles. One of the primary limitations is the degradation of magnetic properties under prolonged radiation exposure. Experimental analyses indicate that magnetic susceptibility decreases due to structural modifications induced by ionizing radiation, which can compromise the long-term effectiveness of these materials [12–14]. Additionally, the uniform dispersion and strong adhesion of nanoparticles within textile fibers are critical factors affecting the overall shielding efficiency, as agglomeration of nanoparticles may reduce their protective performance [15, 16].

To address these challenges, this study explores the comparative shielding effectiveness of magnetic textile composites embedded with Fe_3O_4 nanoparticles. The focus is on evaluating their protective capabilities against charged radiation (alpha and beta particles) and EMI by analyzing frequency-dependent absorption and reflection properties. Furthermore, the experimental analysis of magnetic susceptibility before and after irradiation provides insights into the extent of radiation-induced structural changes and their impact on shielding performance. The findings of this research contribute to the advancement of radiation-resistant textiles, offering a flexible and adaptive solution for protection against multiple types of radiation.

By investigating the magnetic behavior and structural integrity of Fe_2O_3 or Fe_3O_4-modified textiles, this study

aims to enhance the understanding of their potential applications in radiation shielding and to develop strategies for improving their long-term durability and effectiveness. The integration of such innovative materials into everyday protective equipment could revolutionize the field of radiation shielding, making protection more accessible and practical across diverse industries.

2. MATERIALS AND METHODS

2.1. Magnetic Textile Composites

$FeSO_4 \cdot 7H_2O$ was from Penta, Czech Republic and $Na_2CO_3 \cdot 10H_2O$ was from Lachema, Czech Republic. Technical felt TTN (composition: 80% wool, 20% viscose; thickness: 3 mm; density: 0.36 g/cm3) was from Brněnská továrna plstí, s.r.o., Brno, Czech Republic.

Magnetic modification of felt

Felt was magnetically modified using modified direct microwave assisted procedure [17]. Felt was cut to obtain square pieces (6x6 cm), which were then immersed in excess of 20% ferrous sulfate solution for one hour. The modified textile pieces were dried at laboratory temperature for 24 hours and then they were individually put into 250 mL of 10% sodium carbonate solution in one liter beaker and treated in a standard domestic oven (700 W, 2 450 MHz) for 15 min. Then the black colored textile pieces were repeatedly washed with water and dried at laboratory temperature (see Figure 1). The amount of magnetic iron oxide bound to textile was measured as a difference of textile mass before and after treatment.



Fig. 1 Examples of native felt, felt modified with 20% ferrous sulfate solution and magnetic iron oxide particles modified felt (from left to right)

Table 1 The amount of magnetic iron oxide bound to textile

Textile number	Mass before treatment [g]	Mass after treatment [g]	Difference [g]
№0	4.030	4.030	0
№1	3.897	4.062	0.196
№2	4.095	4.291	0.105

Table 1 summarizes the results of the textile modification process by presenting the mass of samples before and after treatment with Fe_3O_4 nanoparticles. The difference in weight reflects the quantity of iron oxide retained within the textile structure. As expected, the control sample (Sample 0), which was not subjected to the modification procedure, showed no measurable change in mass. In contrast, Samples 1 and 2 exhibited a noticeable weight increase, confirming the successful deposition of magnetic material on the fabric surface. These values provide direct evidence of the efficiency of the modification approach and allow for an estimation of the amount of magnetic phase incorporated into the composite.

2.2. Measurement Techniques

To evaluate the protective performance of textile materials modified with magnetic nanoparticles, it is essential to understand the key physical principles behind each measurement technique used. These include magnetic characterization, electromagnetic interference (EMI) shielding, and interaction with radiation. While each of these areas relies on different mechanisms, they are interconnected through the role of magnetic materials in absorbing energy and interacting with external fields.

One of the fundamental physical properties of magnetically modified materials is magnetic susceptibility (χ), which describes how much a material becomes magnetized in response to an external magnetic field. In composites that incorporate magnetic nanoparticles, susceptibility measurements reveal the behaviour of the embedded particles and help determine their potential for interacting with external fields, including electromagnetic radiation. Magnetic susceptibility, particularly when measured across a broad frequency range, can provide valuable insights into relaxation phenomena, particle size effects, and interparticle interactions. It is especially important for detecting dynamic magnetic behaviours such as superparamagnetism, which is often exhibited by nanoparticles due to their small size and thermal fluctuations.

Magnetic susceptibility **(χ)** of the samples was evaluated using a commercial AC susceptometer (IMEGO, DynoMag, Sweden), which operates under ambient laboratory conditions. Measurements were performed across a broad frequency range from 1 Hz to 250 kHz in order to characterize the frequency-dependent magnetic behavior of the materials. The system allows for highly sensitive detection, with a volume susceptibility resolution of 4×10^{-7}, enabling precise analysis of even weakly magnetic samples. An excitation magnetic field with an amplitude of 0.5 mT was applied during the measurements. This amplitude was selected to ensure that the magnetization response remained within the linear region, avoiding magnetic saturation while still providing a detectable signal. The DynoMag susceptometer utilizes a dual-coil detection system and lock-in amplification, which ensures high accuracy and low noise, even at low frequencies. These measurements provide valuable insight into the dynamic magnetic response of the materials, including magnetic relaxation mechanisms and potential superparamagnetic behavior, especially relevant for nanoparticles and functionalized nanostructures.

Another crucial aspect of evaluating functional textiles is their ability to block or attenuate unwanted electromagnetic radiation, known as electromagnetic interference (EMI). This is typically quantified through shielding effectiveness (SE) , which represents how well a material reflects, absorbs, or scatters incident electromagnetic waves [18]. The SE of a material can be

defined as the ratio of the incident field intensity to the transmitted field intensity, expressed in decibels (dB). It is given by:

$$SE = 20\log\left(\frac{E_{incident}}{E_{transmitted}}\right) = 20\log\left(\frac{H_{incident}}{H_{transmitted}}\right)$$

where:

- $E_{incident}$ and $E_{transmitted}$ are the amplitudes of the electric field before and after passing through the shielding material, respectively.
- $H_{incident}$ and $H_{transmitted}$ are the amplitudes of the magnetic field before and after the shield, respectively.

The total shielding effectiveness can be broken down into three major contributions:

$$SE_{total} = SE_R + SE_A + SE_M$$

where:

- SE_R is the reflection loss due to impedance mismatch between the shielding material and free space.
- SE_A is the absorption loss caused by the attenuation of electromagnetic waves within the material.
- SE_M is the multiple reflection loss due to wave interactions inside the material.

For magnetic textiles, shielding effectiveness is primarily determined by the distribution and concentration of embedded magnetic nanoparticles. The effectiveness is also influenced by the thickness of the textile layer and the arrangement of nanomaterials within the fabric structure. Also, attenuation follows a combination of electric and magnetic field absorption mechanisms. The effective permittivity ($\varepsilon*$) and permeability ($\mu*$) of the fabric determine its shielding properties:

$$\varepsilon^* = \varepsilon' - j\varepsilon''$$

$$\mu^* = \mu' - j\mu''$$

where: ε' and μ' – the real parts (energy storage), while ε'' and μ'' – imaginary parts (energy dissipation).

In magnetically functionalized textiles, factors such as permeability, conductivity, and nanoparticle distribution influence the degree of EMI attenuation, especially in near-field environments [19]. The near-field is defined as distances smaller than:

$$r < \frac{\lambda}{2\pi}$$

where: λ – the wavelength of the electromagnetic wave.
In this region, the electric and magnetic fields behave independently, and magnetic permeability plays a dominant role. In contrast, in the far-field, the wave impedance approaches that of free space, and shielding effectiveness is dictated by material conductivity and thickness.

Electromagnetic shielding effectiveness (SE) was evaluated using a near-field measurement technique within the frequency range of 500 MHz to 5 GHz. This method involves placing the test sample between a transmitting and a receiving antenna in close proximity, which allows for the detection of electromagnetic wave attenuation directly influenced by the material's surface and structure. The setup enables the assessment of shielding performance under realistic conditions that closely simulate practical applications, where near-field interactions often dominate. The frequency range was selected to cover typical bands used in wireless communication, including mobile networks, Wi-Fi, and radar systems. Measurements were conducted under controlled laboratory conditions to minimize external noise and ensure repeatability. This approach provides reliable data on how well a material can attenuate or reflect electromagnetic radiation in high-frequency environments, particularly relevant for evaluating lightweight and flexible shielding materials such as modified textiles.

Another important aspect is the material's interaction with ionizing radiation, which includes charged particles and high-energy photons. In this study, the focus is primarily on alpha and beta particles, although gamma rays and conversion electrons also contribute to the overall radiation environment. These types of radiation can cause structural damage to materials and may alter their physical properties. Theoretically, materials containing magnetic nanoparticles may not only attenuate the incoming particles but also influence their paths through local magnetic fields, offering an additional layer of protection.

Accurate assessment of these effects requires the use of specialized instruments. Magnetic susceptibility is measured using high-resolution AC susceptometers operating over a wide frequency range. The effects of ionizing radiation are examined using both electron accelerators, which deliver controlled radiation doses, and radioactive isotope sources such as ^{237}Np and ^{241}Am, which emit alpha particles, beta particles, gamma rays, and conversion electrons. To monitor the radiation dose and exposure, calibrated radiometers are used, ensuring precise control of experimental conditions.

Irradiation was carried out on an electron accelerator M-30 microtron of the Institute of Electron Physics, certified for radiation research (see Figure 2). The M-30 parameters allow one to smoothly regulate accelerated nuclear particles' energy in the range of 1–25 MeV with mono energy of 0.02% and a beam current value of up to 50 μA. Conditions for nuclear irradiation of samples were as follows: irradiation was carried out in the air, at room temperature; the irradiation flux density was 3.1×10^{11} el. (cm^{-2} sec^{-1}) and not lead to heating of the irradiated samples. Irradiation field homogeneity was more than 80%; irradiated procedure was carried three times with doses of 53 kGy, 100 kGy and 163 kGy. The total time of samples irradiation was 40 min. The contribution of associated photoneutrons and bremsstrahlung gamma radiation was monitored and did not exceed 5%. The energy of the 18.5

MeV particles provided the same irradiation conditions for the entire, as the shadow effects were virtually absent.

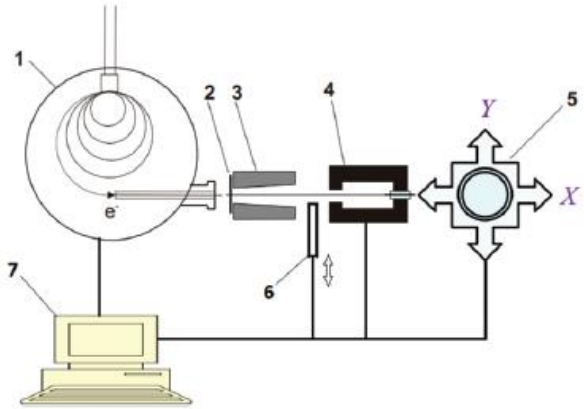


Fig. 2 Scheme of the radiation experiment (1) electron accelerator the M-30 microtron, (2) and (3) irradiation field shaper, (4) Faraday cylinder, (5) the scanner, (6) sample container, (7) the M-30 control and registration panel

At electron energies above 10 MeV, the maximum energy they give to recoil atoms structure of nanomagnetic textured samples exceeds 10^4 eV, which leads to cascades of atomic displacements, which can also be caused by fast neutrons and heavily charged particles. In this case, the irradiated samples have the local disordered regions with significant damage to the structure of molecules and formations of isolated groups of ionized/excited molecular segments and their structural complexes, 'spurs', where the primary acts of magnetic interaction and order of the structure can occur.

Radiation experiments were conducted to study the attenuation of nuclear radiation beams using samples of magnetically modified felt.

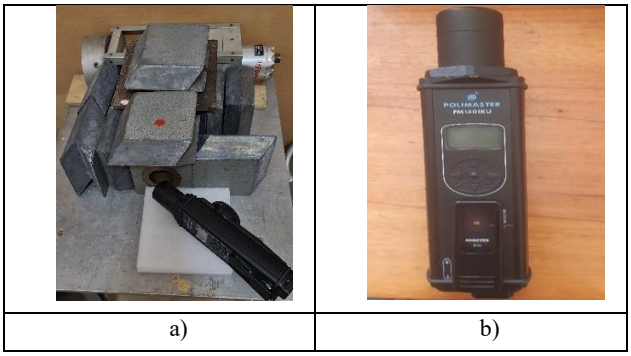
Radiation sources:

- ^{237}Np (source certificate number 237NP-Uni10), activity according to the certificate 1.2×10^8 Bq, decay type α-activity, γ-radiation 0.030 MeV (14%); 0.086 MeV (14%), from now on referred to as source 1. The decay is also accompanied by the emission of γ quanta (and conversion electrons) with energies from 5.5 to 279.7 keV (the most characteristic lines are 29.37 and 86.48 keV with respective probabilities of 14.12% and 12.4%) and X-ray quanta by the daughter ^{233}Pa.

- ^{241}Am (source certificate number 241A-Uni13), activity according to the certificate 1.1×10^{11} (5.0×10^{10}) Bq, decay type α-activity, γ-radiation 0.026 MeV (2.5%); 0.060 MeV (36%), from now on referred to as source 2. The isotope ^{241}Am emits alpha particles during decay, and its daughter nucleus ^{237}Np is the source of a cascade of high-energy g quanta and conversion electrons.

Radiation stand and nuclear radiation detection equipment:

The radiation sources were placed in a radiation stand in the form of a lead house with a collimator (see Figure 3 a) with a diameter of 20 mm, and the exposure conditions on the radiation isotope stands were determined using a certified search radiometer MKC-PM1401K (see Figure 3 b).



a) b)

Fig. 3 (a) radiation stand bench based on radiation sources for studying the shielding properties of magnetically modified felt; (b) radiometer MKS-RM1401K

3. RESULTS AND DISCUSSION

3.1. Magnetic Susceptibility

The magnetic susceptibility (χ) of the samples was measured in the frequency range from 1 Hz to 250 kHz (see Figure 5). A wide frequency range was covered to understand how magnetic susceptibility depends on frequency. This is particularly important for analyzing magnetic particles, whose behaviour can change significantly at high frequencies. Radiation exposure causes defect formation that affects magnetic properties. At low frequencies (1 Hz): High susceptibility is expected, as the magnetic moments of the particles can "follow" changes in the field.

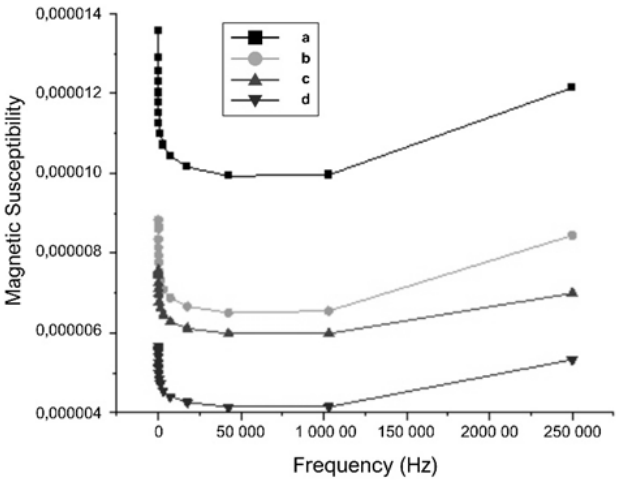


Fig. 4 Magnetic susceptibility of the magnetic iron oxide particles in technical felt (textile №1 - 0.196 g of magnetic particles per 1 textile square):
a: before radiation;
b: after irradiation with dose of 53 kGy;
c: after irradiation with dose of 100 kGy;
d: after irradiation with dose of 163 kGy

At high frequencies (250 kHz): Susceptibility may decrease due to dynamic effects (Néel or Brownian relaxation), especially if the nanoparticles are small.

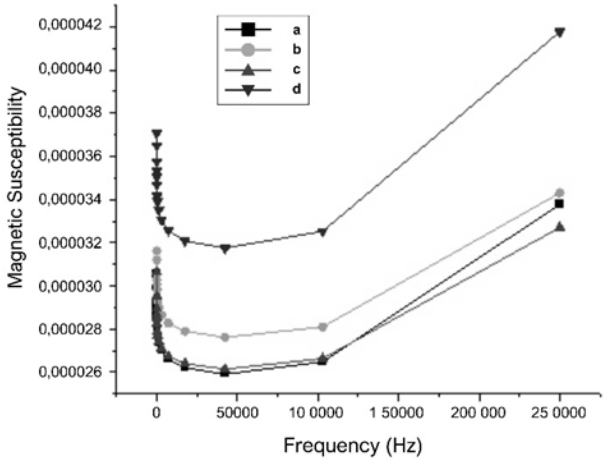


Fig. 5 Magnetic susceptibility of the magnetic iron oxide particles in technical felt (textile №2 - 0.105 g of magnetic particles per 1 textile square):
a: before radiation;
b: after irradiation with dose of 53 kGy;
c: after irradiation with dose of 100 kGy;
d: after irradiation with dose of 163 kGy

As shown in Figure 5, in some cases after radiation exposure, an increase in magnetic susceptibility is observed, suggesting possible structural changes in the nanoparticles that may enhance their magnetic properties. Radiation may influence the structure of the nanoparticles, altering their magnetic behavior and increasing their ability to become magnetically polarized. These changes could be beneficial in the development of more effective radiation-shielding materials, as improved magnetic susceptibility allows for better absorption or reflection of certain types of radiation.

3.2. Shielding Efficiency

Measurements of electromagnetic shielding effectiveness (SE) were conducted in the frequency range from 500 MHz to 5 GHz (see Figure 6) using magnetic textile composites №1 and №2 (see Table 1). The results revealed that the shielding performance was relatively low in several narrow bands, with attenuation values of approximately 1.5 dB in the 880–900 MHz range, 2.9 dB between 930–950 MHz, and again 1.5 dB from 920–930 MHz. In the broader range between 1 GHz and 4 GHz, SE values were negative, around –0.5 dB, suggesting that the material did not effectively absorb incident electromagnetic radiation, and in fact, contributed to partial wave transmission or reflection. A moderate increase in attenuation was observed in the 4–5 GHz range, where SE reached approximately +0.5 dB.

The presence of negative SE values is most likely attributed to multiple internal reflections at the air–textile–air interface. This phenomenon causes a slight amplification of transmitted signal power, which is mathematically interpreted as negative shielding performance.

To enhance the shielding performance of the material, several improvements could be considered. Increasing the concentration or thickness of the magnetic nanoparticle coating may enhance absorption, while optimizing the surface treatment of the textile (e.g., adjusting pH or applying bonding layers) could promote better particle adhesion and homogeneity.

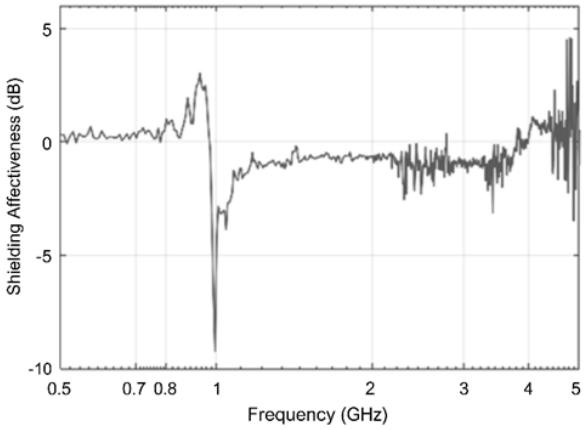


Fig. 6 Shielding effectiveness of the magnetic textile composites №1 (see Table 1)

Furthermore, combining magnetic nanoparticles with conductive additives such as carbon nanotubes or metallic particles may result in synergistic electromagnetic shielding effects. Future studies should also involve angular and polarization-dependent measurements, as anisotropic effects may influence shielding performance in real-world applications. These steps would allow the development of lightweight, flexible, and more efficient shielding materials for use in technical textiles.

3.3. Radiation Shielding

The table below presents detailed results for samples №1 and №2, tested with both radiation sources: ^{237}Np and ^{241}Am. For each case, average radiation intensity was measured in shielded and unshielded conditions. The difference between the two indicates the effectiveness of the textile barrier.

Table 2 Radiation attenuation for samples №1 and №2 under radiation sources

Sample ID	Radiation Source	Shielded Avg (μSv/h)	Unshielded Avg (μSv/h)	Difference (μSv/h)
№1	^{237}Np	49.74	51.00	1.26
№2	^{237}Np	51.71	52.96	1.25
№1	^{241}Am	2.88	2.89	0.01
№2	^{241}Am	2.81	2.84	0.03

The measurements under source ^{237}Np show a clearly measurable shielding effect for both samples. The average reduction in radiation intensity was 1.26 μSv/h for sample №1 and 1.25 μSv/h for sample №2, indicating that these textile composites provide partial attenuation of ionizing radiation. This effect can be attributed to a combination of physical blocking, scattering, and interaction of the radiation with the embedded Fe_3O_4 nanoparticles.

In contrast, the results for source ^{241}Am, which emits predominantly lower-energy alpha particles and associated gamma radiation, showed only minimal differences between shielded and unshielded measurements (0.01–0.03

μSv/h). This is consistent with the known behavior of alpha particles, which are easily stopped by any material surface. The slight differences observed may fall within the uncertainty of the measuring instrument and indicate that, for low-energy radiation, the shielding effectiveness is limited by the material's density and thickness.

This data confirms that radiation exposure can influence the magnetic properties of fabrics modified with iron oxide nanoparticles. While high radiation doses typically lead to degradation—through ionization and atomic displacement that damage magnetic domains—some samples exhibit increased magnetic susceptibility after irradiation. This suggests that radiation may, under certain conditions, induce beneficial structural rearrangements in the nanoparticles, enhancing their magnetic response.

Radiation-induced defects such as vacancies and interstitial atoms usually disrupt domain alignment, but in some cases, they may improve magnetic polarization depending on the material's resilience. If the magnetic modifier remains stable or transforms favorably, magnetic properties may be preserved or even enhanced.

Although these textiles are ineffective against gamma rays and neutrons, the material can still contribute to secondary protection (e.g., thermal shielding, charge decay mitigation).

Magnetically functionalized felts offer multiple advantages: lightweight and flexible shielding: unlike traditional lead-based suits, these materials are breathable and comfortable for long-term wear. Additional protection layer: magnetic nanoparticles may absorb or interact with radiation, making the textile a complementary barrier. Smart textile potential: materials can be engineered to change color, conductivity, or magnetization upon exposure, acting as radiation indicators. Washable and reusable: suitable for repeated use in medicine, nuclear facilities, or emergency scenarios. Cost-effective and scalable: if efficient and affordable, such fabrics could provide mass protection for personnel and civilians in radiation-prone environments.

These findings position magnetic nanoparticle-modified textiles as promising candidates for next-generation, multifunctional radiation protection systems.

4. CONCLUSIONS

This study confirmed the multifunctional potential of magnetic nanoparticle-functionalized textiles as protective materials against both electromagnetic interference (EMI) and ionizing radiation. By integrating Fe_3O_4 nanoparticles into technical modified felts, we successfully created flexible composites that exhibit magnetic activity and measurable shielding properties.

Magnetic susceptibility measurements showed that exposure to radiation does not necessarily degrade the material. In certain cases, it even increased the magnetic response, likely due to internal rearrangements of the nanoparticle structure. This suggests that the fabric may retain or improve its protective properties under prolonged radiation exposure. Electromagnetic shielding effectiveness (SE) was demonstrated in specific frequency bands (notably 880–950 MHz and 4–5 GHz). However, lower SE values in the 1–4 GHz range were observed, potentially caused by multiple internal reflections at the fabric–air interface. Radiation interaction studies confirmed that the textile can partially attenuate alpha and beta particles, particularly from ^{237}Np. As expected, attenuation of low-energy alpha particles from ^{241}Am was minimal due to their limited penetration depth.

To further improve shielding performance, future designs could focus on modifying the composition and internal structure of the textile. This may include:

- increasing the density of magnetic nanoparticles,
- optimizing their distribution within the fibers,
- or applying multiple functional layers to enhance both magnetic and electromagnetic absorption.

In addition, incorporating highly conductive additives such as carbon nanotubes (CNTs) or nano-diamonds could significantly improve EMI shielding by increasing electrical conductivity and enhancing energy dissipation across a wider frequency spectrum. These materials can work synergistically with magnetite to form hybrid composites with superior shielding efficiency. Such modified textile materials may be particularly useful in aerospace and defense, where weight and flexibility are critical, as well as in healthcare settings (e.g., for medical personnel working near imaging equipment), nuclear facilities, or even personal protective clothing for environments with high levels of electromagnetic or radioactive exposure.

In summary, the combination of magnetic nanoparticles with advanced conductive nanomaterials holds promise for developing lightweight, adaptable, and highly effective shielding solutions tailored to specific technical and industrial applications.

ACKNOWLEDGMENTS

This research was supported by the projects No. APVV-22-0060 MAMOTEX and ITMS 313011T548 MODEX (Slovak Research and Development Agency, Ministry of Education, Science, Research and Sport of the Slovak Republic) and the ERDF project No. CZ.02.1.01/0.0/0.0/17_048/0007399 (Ministry of Education, Youth and Sports of the Czech Republic).

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Received May 25, 2025, accepted June 12, 2025

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Volodymyr Maslyuk, Professor, DSc. He obtained a candidate degree in 1978 and a doctoral degree from Chernivtsi State University. In 2006, he received a professor title from the Uzhhorod National University. Areas of scientific interest: electrical and magnetic properties of solids, solid-state radiation physics, nuclear medicine and dosimetry.

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Peter Kopčanský, PhD, Research Professor in condensed matter physics, was born in 1955. He is leading scientist of the Institute of Experimental Physics, SAS. He is working in solid state physics, especially magnetism, magnetic fluids, their magnetic and dielectric properties, composite systems with liquid crystals and technical as well as biomedical applications of magnetic nanoparticles.