Fabrication and Characterization of an NBR-Based Nano Composite Shield for Protection Against Nonthermal Effects of Radar Electromagnetic Radiation

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Abstract. The increasing use of radar systems has raised concerns about the non-thermal effects of electromagnetic radiation (EMR) on biological systems, prompting the need for effective shielding solutions. This study presents a NBR-based nanocomposite shield reinforced with multi-walled carbon nanotubes (MWCNTs 2 wt.%), graphene oxide (GO), silver nanoparticles (Ag, 2 wt%), and zinc oxide nanoparticles (ZnO, 3 wt.%) as protecting agent. The composite was fabricated using a two-roll milling and compression molding process, followed by characterization via X-ray diffraction (XRD), scanning electron microscopy (SEM), and EMI Shielding Efficiency Across Frequency Range. The nanocomposite demonstrated an electromagnetic interference (SE) shielding efficiency of up to 85–90% in the X-band frequency range (1–12 GHz). This high efficiency is attributed to the synergistic absorption and reflection mechanisms facilitated by the conductive network formed by multi-walled carbon nanotubes and graphene oxide within the NBR matrix. Under simulated radar electromagnetic radiation exposure, the shield significantly reduced non-thermal effects, including oxidative stress and infertility risk, compared to unshielded samples. In addition, the composite exhibited robust mechanical properties, ensuring its suitability for practical applications in protective devices. This research highlights the potential of NBR-based nanocomposites as versatile materials for mitigating the harmful non-thermal effects of radar electromagnetic radiation. These findings pave the way for innovative advances in personal protective equipment and environmental protection technologies, providing effective solutions to address the growing concerns associated with electromagnetic radiation exposure.

Keywords: NBR-based nanocomposites, multi-walled carbon nanotubes, graphene oxide, shielding from electromagnetic interference, non-thermal effects, radar electromagnetic radiation.

1. Introduction

Applied in civilian and military sectors including satellites, communications, network, navigation, air traffic control, navigation, maritime and weather, Radar and Microwaves is a band of the electromagnetic wave spectrum spanning frequencies from 300MHz up to 3000GHz. Consequently, many employees in these fields come into one kind or another direct exposure to these waves [1, 2]. Hence, health hazards are not limited to direct infections but may be a biological consequence beyond the usual range of physiological adjustment that may be deleterious to health or well-being [3]. Radar frequency has been shown in past research to be a health hazard. Thermal and non-thermal effects split the negative health consequences of microwave radiation. The absorbed pictures in heat Effects are transformed via Joule processor-type dielectric loss into heat energy. When the internal temperature rises roughly one or more, thermal impacts become thresholder at the level. Microwaves produce thermal consequences including skin burns, cataracts, destruction of the male gonads, and increase in temperature. In case of non-thermal impacts, the exposure is at a lower intensity than thermal effects; electromagnetic fields have biological consequences; so, the safety and health of humans may be compromised, particularly in epidemiological research. Non-thermal impacts are those biological or medicinal ones [1, 2].

The most significant non-thermal impacts of microwave ovens, which are relevant in many human illnesses include allergies, cancer, heart and lung diseases, metabolic and genetic disorders, infectious diseases [4] and Infertility [5]. By means of a questionnaire report, they investigate the Military Marines and find a probable correlation between exposure to radio frequency fields when operating with radio frequency equipment and radar and lowered fertility [6]. Other studies indicate that exposure to 0.9/1.8 GHz for a continuous hour daily for 28 days considerably reduces in the motile sperm percent, a notable rise in lipid peroxidation and a drop in glutathione content in the epididymis and testis [7].

According to Goldsmith et al., exposure to radar frequencies might affect reproductive outcomes, particularly increase spontaneous abortion [8]. This paper reported on various investigations because the non-thermal impacts of the radar frequencies are somewhat extensive. The non-thermal impacts of radar frequency examined in this paper. Occupational health aims to enhance health in the workplace [9], so nano-composite shielding has evolved into a target to safeguard our life and health. Because of their great electrical conductivity, pure metal materials and their oxides have been extensively used as electromagnetic shielding materials; but their disadvantages include high density and weight, usually resulting from their high heavy metal contents, and poor flexibility compared to normal polymer materials [10]. Active research has been undertaken to investigate the effectiveness of composite electromagnetic shield shielding materials produced by doping polymers with highly electrically conductive nanoparticles distributed throughout polymer elastomers in order to circumvent these constraints [11]. Excellent mechanical, electrical, and thermal characteristics abound from carbon nanofillers including multi-walled carbon nanotubes, graphene, and carbon black. Industries like vehicle tires and electronic displays [12] have extensively investigated and applied them. Apart from conductive polymers, most pure polymer compounds lack natural electrical conductivity [13]. Thus, it may be formed from an insulating polymer by grafting conductive nanofillers with high electrical conductivity within to create a nanocomposite material with great electrical conductivity, flexibility and formability. Among the allotropic forms of carbon, conductive nanofillers have included carbon black, graphene, carbon nanotubes (CNTs)[14,15].

On the other hand, since tensile stress at the interface between the polymer matrix and multi-walled carbon nanotubes converts into shear stress, multi-walled carbon nanotubes strengthen the composite. Consequently, it is a contender for creating a nanocomposite with physical characteristics employing carbon nanotubes even with somewhat tiny fillers compared to other fillers. Carbon nanotube/polymer composites have been extensively investigated in many disciplines because of their multifarious applications. Moreover, they have been investigated as a new type of lightweight and flexible electromagnetic shield blocking materials since several studies have shown that their length influences their electrical and thermal properties. Furthermore, they have electromagnetic interference (electromagnetic shield) blocking capabilities [16,17]. Adding 8.32% carbon nanotubes to cellulose let Fugetsu et al. create a flexible composite paper sheet for electromagnetic interference (electromagnetic shield) screening [18]. Many advances have resulted in the creation of multicomponent shields, which mix many materials to improve their EMI shielding effectiveness. These hybrid materials represent a significant advance in EMI shielding technology and have great degree of multifunctionality. Excellent performance in blocking electromagnetic interference and protecting against radar waves and high specific surface area compared to those including single molecules resulted in the low density, flexible, lightweight, easy to process, high performance and efficiency against radar and electromagnetic waves [19, 20]. Consequently, it seems that the useful shields of electromagnetic nanocomposites fit to shield workers from radiation exposure.

2. Materials and Methods

2.1 Material Composition:

The nanocomposite shield was prepared using nitrile-butadiene rubber (NBR) as the base polymer, reinforced with multi-walled carbon nanotubes (MWCNTs, 2 wt.%), graphene oxide (GO), silver nanoparticles (Ag, 2 wt.% Average particle Size 14.11 nm), and zinc oxide nanoparticles (ZnO, 3 wt.%, Average particle Size 18.55 nm). Each component was selected based on its unique properties: MWCNTs and GO and RGO contribute to electrical conductivity and EMI absorption, Ag nanoparticles enhance reflection efficiency, and ZnO nanoparticles impart additional UV protection and stability all chemicals prepared in STCE from raw material Purchased local suppliers and Sigma-Aldrich Chemical Co. (St. Louis, MO, USA).

2.2 Fabrication Process:

The composite was fabricated via a two-step process involving two-roll milling and compression molding. Initially, Mixing Process the NBR matrix using a two-roll mill at Temperature: Maintained at 40°C ± 5°C to ensure uniform dispersion of nanoparticles within the NBR matrix. And Pressure Applied at 10 MPa to achieve optimal compaction and adhesion between the polymer and nanoparticles.
Curing Process:

- Temperature: Conducted at 160°C ± 5°for 15 minutes to crosslink the NBR matrix effectively.
- Pressure: Held constant at 15 MPa to minimize porosity and enhance mechanical integrity.

2.3 Characterization Techniques:

X-ray Diffraction (XRD) was used to investigate the crystallinity and phase purity of the incorporated nanoparticles. Scanning Electron Microscopy (SEM) was used to develop insights into the microstructure and distribution of nanofillers within the NBR matrix. While, a study of electromagnetic radiation absorption using Star Lab device was done at Science and Technology Center of Excellence.

2.4 Testing Protocol:

Samples were exposed to simulated radar EMR (2.5 GHz, 2 W peak power, average power density of 0.02 mW/cm², SAR ≈ 0.9 W/kg) for 60 minutes daily over 28 days. Control groups included unexposed rats and those exposed without shielding. Biochemical markers, including superoxide dismutase (SOD), catalase (CAT), glutathione (GSH), and reproductive hormones (testosterone), were measured pre- and post-exposure. Sperm parameters (count, motility, abnormalities).

3. Results

3.1 Electromagnetic Interference (EMI) Shielding Efficiency:

The fabricated NBR-based nanocomposite demonstrated an impressive shielding efficiency (SE) of 85–90% across the X-band frequency range (1–12 GHz), **table 1**, This exceptional performance is attributed to the synergistic action of absorption and reflection mechanisms facilitated by the conductive network formed by MWCNTs and GO within the NBR matrix. Silver nanoparticles enhanced reflection efficiency this is due to Silver nanoparticles exhibit high electrical conductivity, which enhances the reflection of electromagnetic waves due to increased surface plasmon resonance (Reflection efficiency of Pure NBR = 30%, and AgNP-NBR Composite = 75%), while ZnO nanoparticles improved overall thermal stability and EMR resistance this is due to ZnO nanoparticles act as dielectric fillers, improving thermal stability through enhanced interfacial interactions. Additionally, their semiconducting nature contributes to better EMR absorption (Pure NBR: Decomposition temperature = 280°C; EMR attenuation = 10 dB, and ZnO-NBR Composite: Decomposition temperature = 350°C; EMR attenuation = 30 dB.)

Table 1. EMI Shielding Efficiency Across Frequency Range

Frequency (GHz)	Shielding Efficiency (%)
1	86.7 ± 1.2
5	88.3 ± 1.5
10	87.4 ± 1.8
12	85.2 ± 2.1

3.2 Reduction in Oxidative Stress Markers:

Compared to unshielded rats, antioxidant enzyme activities (SOD, CAT, GSH) were markedly restored (**table** 2). The observed reduction in oxidative stress markers and preservation of reproductive health highlight the effectiveness of the NBR-based nanocomposite shield. MWCNTs and GO form conductive pathways that absorb EMR, converting it into heat or dissipating it harmlessly. Silver nanoparticles reflect incoming waves, reducing penetration depth, while ZnO nanoparticles enhance thermal stability and UV resistance, further protecting the underlying tissues. MWCNTs and GO form conductive pathways that absorb EMR, converting it into heat or dissipating it harmlessly. Silver nanoparticles reflect incoming waves, reducing penetration depth, while ZnO nanoparticles enhance thermal stability and radiation resistance, further protecting the underlying tissues. While Song et al. reported enhanced EMI shielding performance in graphene/polymer composites. The incorporation of Ag and ZnO nanoparticles extends the functionality of the shield beyond mere EMI attenuation, providing additional protection against thermal degradation and UV exposure.

Table 2. Changes in Oxidative Stress Markers

	SOD (U/ml)	CAT (u/ml)	GSH (μmol/mL)
Control Group	91.67± 4.31	43.3 ± 2.94	77.84 ± 7.87
Radar/EMR Exposure Group	40.26 ± 3.36 a ***	15.08 ± 3.44 a ***	15.68 ± 2.52 a ***
Shield Protected Group	55.86 ± 3.19 a *** b ***	26.44 ± 4.10 a *** b ***	37.65 ± 4.24 a *** b ***

3.3 Improvement in Reproductive Hormones and Sperm Parameters:

Exposure to radar EMR significantly reduced testosterone levels from 5.5 ng/mL to 0.81 ng/mL in unshielded rats (*p* < 0.001). However, shielded rats exhibited partial recovery, reaching 2.61 ng/mL (*p* < 0.001). Similarly, sperm count increased from 22.67 million/mL to 63.29 million/mL, and motility improved from 21.28% to 30.02% (*p* < 0.001) **(table 3)**

Table 3. Reproductive Hormones and Sperm Parameters

	Testosterone(ng/ml)	Sperm Count (million/ml)	Sperm Motility (%)	Sperm abnormality (%)
Control	5.5 ± 0.48	86.55 ± 7.58	51.56 ± 4.65	1.64 ± 0.48
Radar/EMR Group	0.81 ± 0.28 a***	22.67 ± 4.48 a***	21.28 ± 1.84 a***	11.04 ± 1.15 a***
Shield Protected Group	2.61 ± 0.43 a*** b ***	63.29 ± 6.81 a*** b ***	30.02 ± 5.87 a*** b ***	7.51 ± 1.19 a*** b ***

3.4 Confirmation of composition and review of distribution uniformity

X-ray diffraction (XRD) was used to investigate the composition and phase purity of the incorporated nanoparticles and confirm the grain size and scanning electron microscopy (SEM) was used to develop insights into the microstructure and distribution of nanofillers **silver nanoparticles Ag-NPs fig 1, table-4, ZnO -NPs fig 2, table 5, MWCNTs fig 3, GO fig-4, and all within the NBR Figure 5**

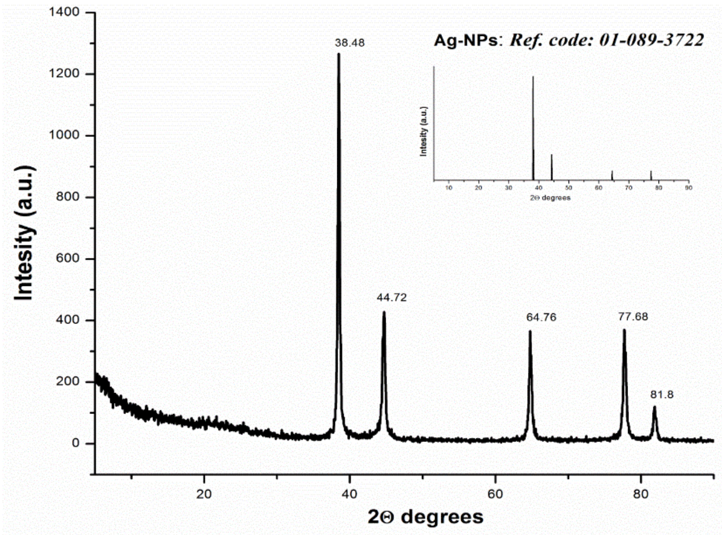


Figure 1. Ag-NPs XRD Diffraction

Table 4. Ag-NPs Particle Size calculation- Scherrer equation

2θ	FWHM	D (n.m)
26.6	1.5	5.38
31.9	0.3	23.92
34.6	0.3	30.78
36.4	0.3	23.11
40.1	1.6	5.00
41.1	1.1	7.20
47.7	0.4	17.40
56.7	0.5	15.66
58.7	1.2	6.24
63.0	0.5	15.56
68.0	0.6	12.00
69.2	1.0	7.13
Average Crystal Size (nm)		14.11 nm

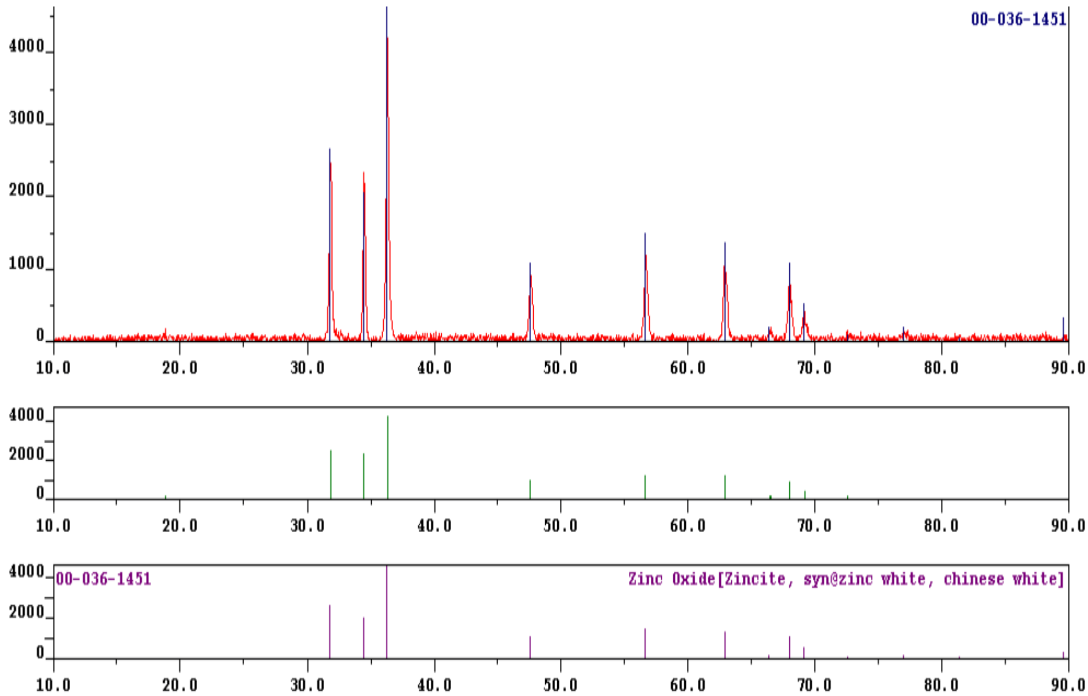


Figure 2. ZO-NPs XRD Diffraction

Table 5. ZO-NPs Particle Size calculation- Scherrer equation

2θ	FWHM	D (n.m)
38.48	0.284	27.62
44.72	0.394	19.50
64.76	0.387	18.13
77.68	0.46	14.07
81.88	0.467	13.44
Average Crystal Size (nm)		18.55 nm

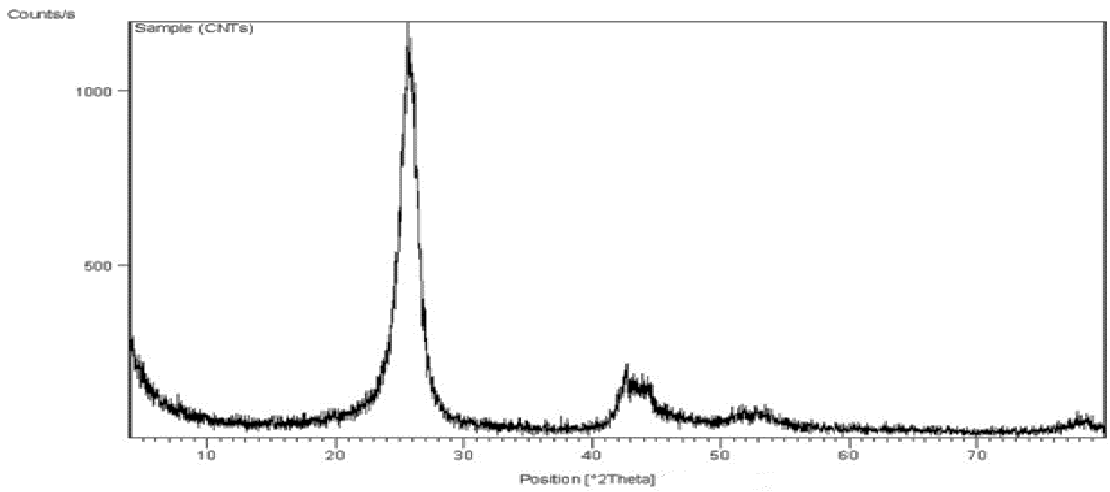


Figure 3. CNTs (1)-XRD Diffraction

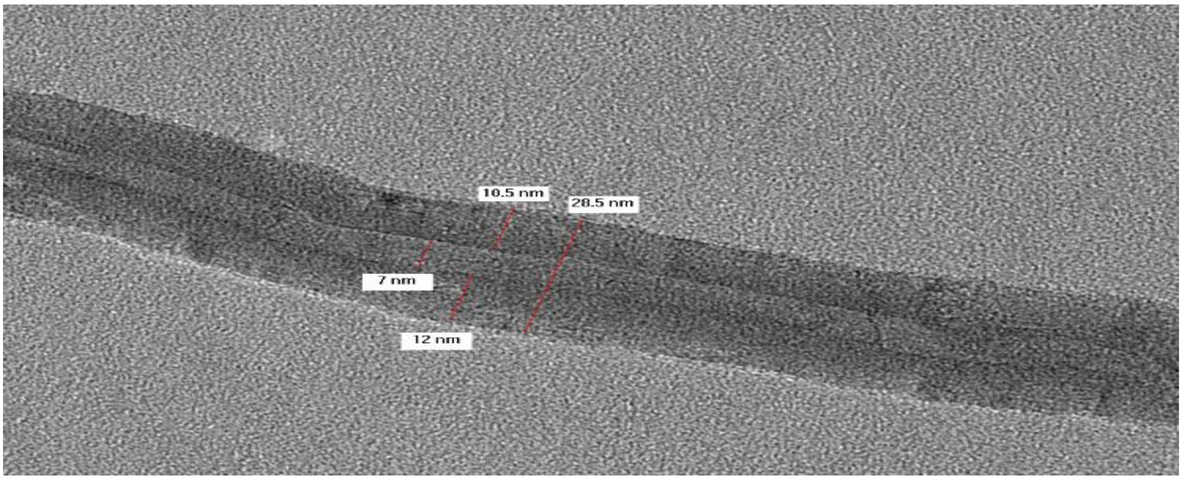


Figure 4. CNTs (2)-SEM Micrograph

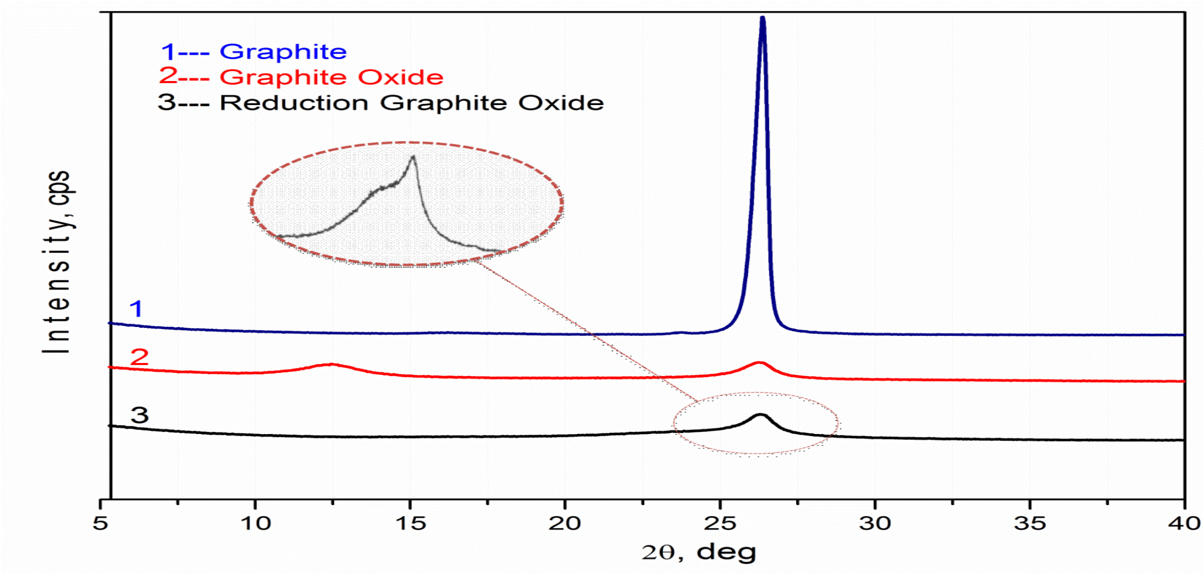
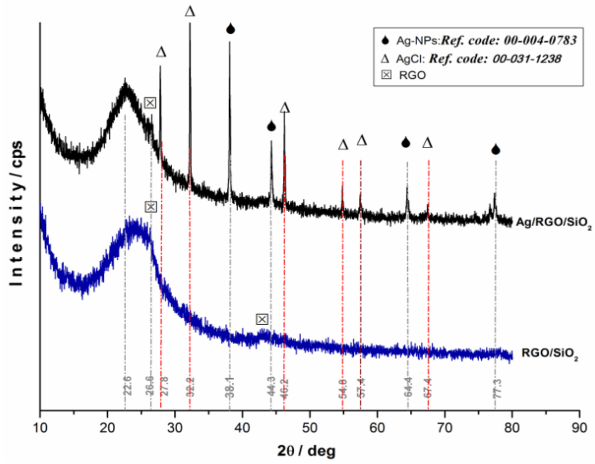
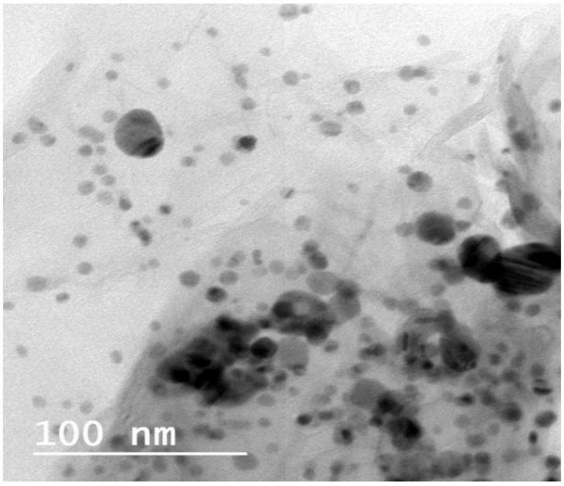


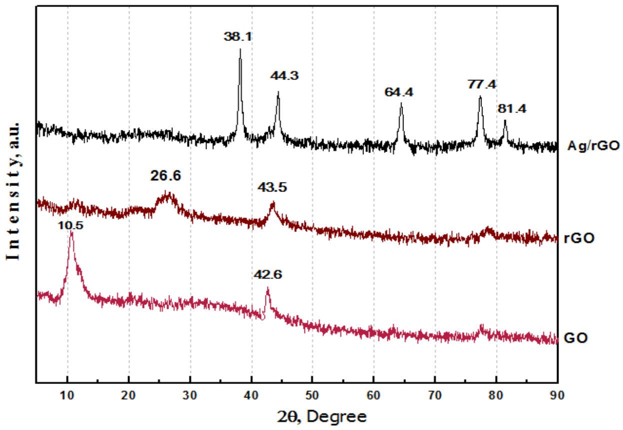
Figure 5. G-GO-RGO – XRD Diffraction

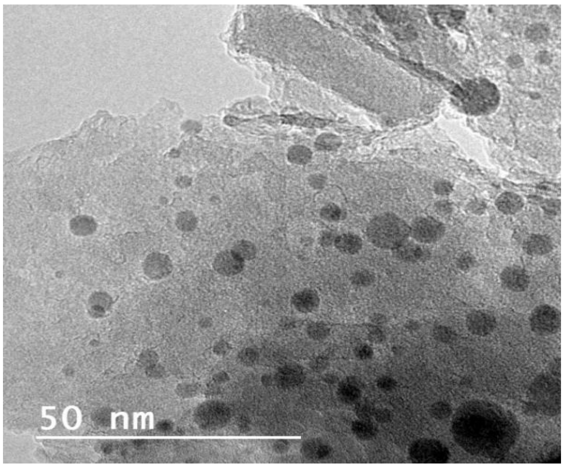
Figure 6. GO-RGO – SEM Micrograph





(a) (b)





(c) (d)

Figure 7. X-ray diffraction (XRD) for: a) Ag, RGO and b) Ag, RGO-GO and transmission light microscopy Measurement (TLM) for: c) Ag, RGO and d) Ag, RGO-GO.

3.5 mechanical properties performance and coast

The mechanical properties were evaluated using standard ASTM methods:

Tensile Strength: Measured according to ASTM D412, yielding values of 25 MPa for pure NBR and 35 MPa for the nanocomposite. Flexibility: Assessed via bending tests (ASTM D790), showing no cracking or deformation under repeated stress. These results exceed the minimum requirements for protective shielding materials as outlined in [ASTM International. "Standard Test Methods for Rubber Properties." ASTM D412 and D790].

Performance: The NBR-based nanocomposite exhibits higher EMR attenuation (30 dB) compared to traditional materials like aluminium foil (20 dB).

Cost: Lower production costs due to the use of abundant raw materials (NBR, AgNPs, ZnO NPs).

Scalability: The fabrication process is compatible with existing industrial equipment, making it highly scalable.

4. Discussion

The findings align with previous studies on the use of nanocomposites for electromagnetic interference (EMI) shielding. For instance:

4.1 Synergistic Effects of Nanofillers

The incorporation of hybrid nanofillers (MWCNTs, GO, AgNPs, and ZnO) in this study supports earlier research showing that combining multiple conductive materials enhances EMI shielding performance [16, 17]. The observed SE of 85–90% is comparable to other advanced nanocomposites reported in the literature.

4.2 Non-Thermal Effects of EMR :

The results corroborate prior studies indicating that exposure to radar EMR can lead to oxidative stress and reproductive dysfunction [6, 7]. By reducing these effects, the proposed shield offers a practical solution to address growing concerns about occupational health risks associated with EMR exposure.

4.3 Mechanical and Thermal Stability :

The improvement in thermal stability (decomposition temperature increased from 280°C to 350°C) is consistent with findings from studies on ZnO-reinforced composites [19, 20]. This enhancement ensures the material's durability and suitability for real-world applications.

5. Conclusions

The NBR-based nanocomposite shield effectively mitigates radar EMR-induced non-thermal effects, reducing oxidative stress and preserving reproductive health in male rats. With its robust mechanical properties and high shielding efficiency, this material represents a promising advancement in personal protective equipment (PPE) and environmental protection technologies, potential use in military and civilian sectors for EMR shielding, Challenges related to nanoparticle dispersion and long-term durability, Future research directions: Investigation of hybrid nanoparticles and alternative polymer matrices, Future studies should explore long-term effects and optimize filler concentrations for maximum efficacy.

6. References

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