Supporting Information
(Including 27 Pages, 7 Figures, and 4 Tables)

NiFe$_2$O$_4$ Nanoparticles Synthesized by Dextrin from Corn-mediated Sol-Gel Combustion Method and its Polypropylene Nanocomposites Engineered with Reduced Graphene Oxide for the Reduction of Electromagnetic Pollution

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Synthesis of Graphene Oxide (GO)

1.5 g graphite powder and 1.5 g sodium nitrate was mixed with 75 ml of H$_2$SO$_4$. After slow addition of 9g of potassium permanganate, the solution was stirred under an ice bath for 30 min. This solution was further stirred for 48 h at room temperature. The solution was stirred with addition of 138 ml deionized water for 10 min. Then, 420 ml warm deionized water and 30 ml H$_2$O$_2$ were added and stirred until the solution become gold color. Finally, the solution was centrifuged and washed with deionized water. The obtained GO was annealed at 60 °C in vacuum oven.

Williamson-Hall Method and Structural Parameter Study

Further, the crystallite size and micro-strain was evaluated by Williamson-Hall Method$^1$. The measured diffraction width ($\beta$) can be expressed as$^2$:

$$\beta_{hkl} = \beta_D + \beta_S = \frac{k\lambda}{D \cos \theta} + 4 \varepsilon \tan \theta$$

**Figure S1**: Williamson-Hall plots for NiFe$_2$O$_4$ nanoparticles,
where $\beta_D$ and $\beta_S$ are the contributions to the diffraction broadening from grain size and strain, respectively; $\theta$ is the X-ray diffraction Bragg angle, $\varepsilon$ is the micro-strain, and $D$ is the grain size. Above equation can be re-expressed as:

$$\beta_{hkl}\cos\theta = \varepsilon (4 \sin\theta) + k\lambda/D$$

This equation symbolizes a linear relationship between $\beta_{hkl}\cos\theta$ and $4\sin\theta$. The plot between $\beta_{hkl}\cos\theta$ (as y-axis) and $4\sin\theta$ (as x-axis) provides the strain through the slope of the line and particle size ($D$) can be evaluated from the intercept ($= \lambda/D$) of the line (on the y axis).

Figure S1 presents the variation of $\beta_{hkl}\cos\theta$ with $4\sin\theta$ and it was linear for NiFe$_2$O$_4$ nanoparticles annealed at 600 °C, 800 °C, and 1000 °C. The strain was evaluated by extrapolated and obtained a straight line to the y axis. The evaluated strain and crystallite size of nanoparticles are mentioned in Table S1. The evaluated particle size was 19.6, 32.8, 61.3 nm for NiFe$_2$O$_4$ nanoparticles annealed at 600 °C, 800 °C, and 1000 °C, respectively.

**Table S1: Structural parameters for nickel ferrite nanoparticles**

| Sample → Structural Parameters ↓ | NFD@600 | NFD@800 | NFD@1000 |
|---------------------------------|---------|---------|-----------|
| **Annealing Temperature ( °C)** | 600 °C  | 800 °C  | 1000 °C   |
| Debye Scherrer Crystalline Size D ( nm ) | 20.6    | 34.5    | 68.6      |
| Williamson Method Crystallite Size D (nm) | 19.6    | 32.8    | 61.3      |
| Strain (%) | 1.9x10^{-3} | -1.4x10^{-4} | -4.9x10^{-4} |
| **Lattice parameter a (Å)** | 8.3363  | 8.3431  | 8.3490    |
| **X-ray Density d_x ( g/cm$^3$)** | 5.374   | 5.361   | 5.349     |
| **Ionic radii** | | | |
| $r_A$ (Å) | 0.5714  | 0.5729  | 0.5743    |
| $r_B$ (Å) | 0.7141  | 0.7157  | 0.7172    |
| **Hopping Length** | | | |
| $d_A$ (Å) | 3.6096  | 3.6125  | 3.6151    |
| $d_B$ (Å) | 2.9468  | 2.9493  | 2.9514    |
| **Tet.Bond d_{AX} (Å)** | 1.8914  | 1.8929  | 1.8943    |
| **Oct. Bond, d_{BX} (Å)** | 2.0352  | 2.0369  | 2.0383    |
| **Tet. Edge d_{AXE} (Å)** | 3.0883  | 3.0908  | 3.0930    |
| **Oct.Edge ( shared & unshared)** | | | |
| $d_{BXE} (Å)$ | 2.8054  | 2.8077  | 2.8097    |
| $d_{BXEU} (Å)$ | 2.9490  | 2.9514  | 2.9535    |
The lattice parameter of prepared nanoparticles was evaluated by utilizing following relation S3:

\[ a = \frac{\lambda (h^2 + k^2 + l^2)^{1/2}}{2 \sin \theta} \]

The evaluated values of lattice parameter are mentioned in Table S1. It is observed that the lattice parameter was increased with annealing temperature. The X-ray density (\(\rho_{\text{X-ray}}\)) of prepared NiFe\(_2\)O\(_4\) nanoparticles was evaluated by using following relation S4:

\[ \rho_{\text{X-ray}} = \frac{ZM}{N_A a^3} \]

where, Z is the number of molecules per unit cell (Z = 8 for spinel structure), M is the molecular weight, \(N_A\) is the Avogadro’s number and ‘a’ is the lattice parameter. The evaluated values of X-ray density of the nanoparticles are mentioned in Table S1.

The structural parameters such as the tetrahedral and octahedral site radii (\(r_A\) and \(r_B\)), hopping length in tetrahedral and octahedral site (\(d_A\) and \(d_B\)), tetrahedral and octahedral bond lengths (\(d_{Ax}\) and \(d_{Bx}\)), tetrahedral edge, shared and unshared octahedral edges (\(d_{AxE}, d_{BxE}\) and \(d_{BxEU}\)) can be evaluated by using following relation S5-S6:

\[ r_A = \left( u - \frac{1}{4} \right) a\sqrt{3} - R_o \]

\[ r_B = \left( \frac{5}{8} - u \right) a - R_o \]

\[ d_A = \frac{1}{4} a\sqrt{3} \]

\[ d_B = \frac{1}{4} a\sqrt{2} \]

\[ d_{Ax} = a\sqrt{3} \left( u - \frac{1}{4} \right) \]
\[
\begin{align*}
    d_{Bx} &= a \left[ 3u^2 - \left( \frac{11}{4} \right)u + \left( \frac{43}{64} \right) \right]^{1/2} \\
    d_{AXE} &= a\sqrt{2} \left( 2u - \frac{1}{2} \right) \\
    d_{BXE} &= a\sqrt{2} (1 - 2u) \\
    d_{BxEU} &= a \left[ 4u^2 - 3u + \left( \frac{11}{16} \right) \right]^{1/2}
\end{align*}
\]

where, \(a\) is the lattice parameter, \(u\) is the oxygen positional parameter (\(u = 0.381\ \text{Å}\)), and \(R_o\) (\(= 1.32\ \text{Å}\)) is the radius of the oxygen. The evaluated values of structural parameters are mentioned in Table S1. It can be noticed that the hopping length increases with increases with annealing temperature. It signifies that the distance between the magnetic ions increases with increase of annealing temperature. It is associated with increase of particle size and cation redistribution with annealing temperature. The variation in structural parameters can lead the change in physical properties of NiFe\(_2\)O\(_4\) nanoparticles.

**FE-SEM Study of NiFe\(_2\)O\(_4\) Nanoparticles**

The FE-SEM image of prepared nanoparticles are shown in Figure S2 (a-c). It can be noticed that NFD@600 nanoparticles have spherical morphology with particle size 10-25 nm. However, NFD@800 and NFD@1000 nanoparticles have cuboctahedra-like morphology with particle size 20-60 nm and 50-110 nm, respectively. Figure S2(d) depicts the typical EDX spectrum of NFD@600 sample, which confirm the presence of Ni, Fe and O elements in nickel ferrite nanoparticles. Figure S2 (e) displays the FE-SEM image of prepared graphene oxide, which shows a crumpled flaky structure. Figure S2 (f) presents the FE-SEM image of prepared reduced graphene oxide (rGO), which exhibits folded and wrinkled morphology. EDX
spectrum of reduced graphene oxide is shown in Figure S2(g), which indicate existence of 85% carbon and 15% oxygen in terms of atomic percentage.
**Figure S2:** FE-SEM image of (a) NFD@600 (b) NFD@800 (c) NFD@1000, (d) representative EDX spectrum of NFD@600, (e) FE-SEM image of graphene oxide, (f) FE-SEM image of reduced graphene oxide, and (g) EDX spectrum of reduced graphene oxide.

**Raman Spectroscopy Study**

Raman spectroscopy is an important tool to investigate the structural characteristics of nanoparticles and nanocomposites. **Figure S3 (a & b)** present the Raman spectra of reduced graphene oxide and graphene oxide. The Raman spectra of reduced graphene oxide exhibit the D band at 1350 cm\(^{-1}\) and G band at 1591 cm\(^{-1}\), which confirm the lattice distortion. However, for graphene oxide, the appearance of D band was at 1341 cm\(^{-1}\) and G band at 1600 cm\(^{-1}\). Herein, the D and G band of reduced graphene oxide were slightly shifted in comparison with band position of graphene oxide. The G band is associated with the E\(_{2g}\) phonon of the sp\(^2\) C atoms and the D band is related to the breathing mode of k-point phonons of A\(_{1g}\) symmetry. Further, the D band signifies the disorder associated with certain defects such as vacancies, grain boundaries, and amorphous carbon species. In addition, the ratio of I\(_D\)/I\(_G\) peaks intensity symbolises the quality of this material. The ratio of I\(_D\)/I\(_G\) peaks intensity were 0.84 and 1.10 for graphene oxide and reduced graphene oxide, respectively. It signifies the reduction of average size of sp\(^2\) domains and the surface chemical impurities/edge defects.

**Figure S3 (c)** represents the Raman spectra of synthesized nickel ferrite nanoparticles, namely (i) NFD@600, (ii) NFD@800, and (iii) NFD@1000 sample. The prepared NiFe\(_2\)O\(_4\) nanoparticles crystallizes in spinel ferrite crystal structure and theoretical group analysis predicts the five Raman active mode, A\(_{1g}\)+E\(_g\)+3T\(_{2g}\). In synthesized nickel ferrite nanoparticles, the strongest Raman band A\(_{1g}\) at about 690 cm\(^{-1}\) is related to symmetric stretching of oxygen in tetrahedral AO\(_4\) groups. The Raman band E\(_g\) at about 332 cm\(^{-1}\) corresponds to symmetric bending of oxygen with respect to cation in tetrahedral site. Further, the Raman band T\(_{2g}(2)\) at about 481
cm\(^{-1}\) is related to asymmetric stretching and the Raman band T\(_{2g}(3)\) at about 566 cm\(^{-1}\) is associated with asymmetric bending of oxygen \(^{S13}\). Furthermore, the Raman band T\(_{2g}(1)\) at about 206 cm\(^{-1}\) is caused by translational movement of the entire tetrahedron \(^{S14}\). **Figure S3 (d)** presents the Raman spectra of prepared nanocomposites, namely (i) NFD@600-rGO-PP, (ii) NFD@800-rGO-PP, and (iii) NFD@1000-rGO-PP. The prepared nanocomposites exhibited D band at about 1350 cm\(^{-1}\) and G band at about 1591 cm\(^{-1}\) corresponding to existence of the reduced graphene oxide in the PP matrix and also the all the fundamental Raman band of NiFe\(_2\)O\(_4\) nanoparticles at 329 cm\(^{-1}\) corresponding to E\(_g\) mode, the band at about 795 cm\(^{-1}\) corresponding to A\(_{1g}\), and the bands at 565 cm\(^{-1}\), 478 cm\(^{-1}\), 201 cm\(^{-1}\) corresponding to T\(_{2g}\) mode \(^{S15}\). The Raman bands corresponding to PP matrix can be noticed in **Figure S3 (d)**, from 800 cm\(^{-1}\) – 3500 cm\(^{-1}\) \(^{S16}\).
Figure S3: Raman spectroscopy of (a) reduced graphene oxide, (b) graphene oxide, (c) prepared nanoparticles, and (d) prepared nanocomposites.

FTIR Spectroscopy Study

Figure S4 depicts FTIR spectra of graphene oxide, reduced graphene oxide, prepared nanoparticles and nanocomposites. The graphene oxide as shown in Figure S4 (a) consists of the bands at ca. 1044 cm\(^{-1}\) (C-O), 1386 cm\(^{-1}\) (C-O), 1596 cm\(^{-1}\) (C=C), 1727 cm\(^{-1}\) (C=O) and 3355 cm\(^{-1}\) (O-H)\(^{S17-S19}\). The reduction of GO can be noticed in FTIR spectra of RGO as shown in Figure S4 (a). The intensity related to oxygen functional groups was decreased after reduction of GO. Figure S4 (b) presents FTIR spectra of prepared nanoparticles. FTIR spectra of spinel ferrite consists of mainly two vibrational bands. One vibrational band around 500-600 cm\(^{-1}\) is related to the stretching vibration of tetrahedral groups and the second one around 300-400 cm\(^{-1}\) is associated with the stretching vibration of octahedral groups\(^{S20}\). The band corresponding to the stretching vibration of tetrahedral groups was 543, 530 and 523 cm\(^{-1}\) for NFD@600, NFD@800, and NFD@1000, respectively. In addition, the band corresponding to the stretching vibration of octahedral group was 317 cm\(^{-1}\), 311 cm\(^{-1}\) and 309 cm\(^{-1}\), for NFD@600, NFD@800, and NFD@1000, respectively. This variation in two bands are associated with the cation redistribution at octahedral and tetrahedral site in spinel ferrite\(^{S21-S22}\).

Further, Figure S4 (c) depicts FTIR spectra of prepared nanocomposites. The FTIR spectra of nanocomposites consist of vibrational bands at about 2830-2961 cm\(^{-1}\), 1458 cm\(^{-1}\), 1379 cm\(^{-1}\) and 540 cm\(^{-1}\). The bands 2830-2961 cm\(^{-1}\) is associated with stretching vibration of -C-H group of PP, 1458 cm\(^{-1}\) is related to the bending vibration of -CH\(_2\) group for PP, 1379 cm\(^{-1}\) is related
with bending vibration of -CH$_3$ group for PP and 540 cm$^{-1}$ is associated with the stretching vibration of tetrahedral group for nickel ferrite nanoparticles $^{523}$.

**Figure S4:** FTIR spectra of (a) graphene oxide and reduced graphene oxide, (b) prepared nickel ferrite nanoparticles, (c) prepared nanocomposites

**X-ray Photoelectron Spectroscopy Study**

The oxidation state of Ni and Fe in prepared nickel ferrite nanoparticles is confirmed by XPS. In addition, percentage of presence of Ni and Fe at octahedral and tetrahedral site in spinel ferrite nanoparticles is evaluated. **Figure S5 (a)** displays the XPS survey spectrum of NFD@600, which represents the presence of Ni 2p, Fe 2p and O 1s peaks at binding energies
(BE) of 854.5, 708.9, and 530.8 eV, respectively. Further, the presence of Ni 2s and Fe 2s is noticed at lower binding energy, as shown in Figure S5 (a).

Figure S5: (a) XPS survey spectrum of NFD@600, (b) Deconvoluted XPS spectrum of Ni for NFD@600, (c) Deconvoluted XPS spectrum of Fe for NFD@600, (d) XPS survey spectrum of NFD@1000, (e) Deconvoluted XPS spectrum of Ni for NFD@1000, (f) Deconvoluted XPS spectrum of Fe for NFD@1000.
In addition, **Figure S5 (b & c)** displays the deconvoluted spectra of Ni 2p and Fe 2p peaks, respectively, of prepared NFD@600 sample. **Figure S5 (b)** displays the presence of Ni 2p_{3/2} and Ni 2p_{1/2} at binding energy 854.8 eV and 872.4 eV, respectively, and satellite peak associated with Ni 2p_{3/2} at 861.6 eV, which indicates the presence of Ni^{2+} cation in NFD@600 sample. Further, **Figure S5 (c)** represents existence of Fe 2p_{3/2} and Fe 2p_{1/2} at binding energy at 710.8 eV and 724.2 eV, respectively, with satellite peak for Fe 2p_{3/2} at 719.4 eV, which confirms existence of Fe^{3+} cations in NFD@600 sample. **Figure S5 (d)** displays the XPS survey spectrum of NFD@1000, which has similar features as NFD@600 samples. The existence of Ni 2p_{3/2} and Ni 2p_{1/2} at binding energy 854.8 eV and 872.8 eV, respectively, with presence of satellite peak at 861.4 eV corresponding to Ni 2p_{3/2} for NFD@1000, is shown in **Figure S5 (e)**. Furthermore, **Figure S5 (f)** displays presence of Fe 2p_{3/2} and Fe 2p_{1/2} at binding energy at 711.3 eV and 724.5 eV, respectively, corresponding to satellite peak for Fe 2p_{3/2} at 718.6 eV, which indicates the presence of Fe^{3+} cations in NFD@1000. The Fe and Ni region was further fitted and analyzed for the presence of cations at octahedral and tetrahedral site in nickel ferrite nanoparticles. For NFD@600 sample, the existence of Ni^{2+} at octahedral and tetrahedral site are 72% and 28%, respectively. In this sample, the presence of Fe^{3+} at octahedral and tetrahedral site are 58% and 42%, respectively. For NFD@1000 sample, the existence of Fe^{3+} at octahedral and tetrahedral site are 67% and 33%, respectively. However, Ni^{2+} at octahedral and tetrahedral site are 59% and 41%, respectively. The quantitative analysis indicates the degree of inversion of cation in nickel ferrite nanoparticle with change of particle size. Further, the occupation formula from XPS study for NFD@600 and NFD@1000 sample is $\left( \text{Ni}_{0.58}^{2+}\text{Fe}_{0.42}^{3+} \right) \left[ \text{Ni}_{0.72}^{2+}\text{Fe}_{0.28}^{3+} \right]$ and $\left( \text{Ni}_{0.51}^{2+}\text{Fe}_{0.49}^{3+} \right) \left[ \text{Ni}_{0.59}^{2+}\text{Fe}_{0.41}^{3+} \right]$, respectively. **Figure S6** shows the XPS survey spectra and high resolution XPS spectra of GO and rGO. It can be noticed from the XPS survey spectra (**Figure S6 a & c**) that the peak intensity of O 1s for rGO decreases after reduction of GO. The high resolution XPS spectra of GO for C1s
(Figure S6 b) was fitted with five XPS peaks associated with various carbon species such as hydrocarbon (C=C) at 284.1 eV, (C-C/C-H) at 284.8 eV, hydroxyl (C-OX) at 286.6 eV, carbonyl (C=O/O-C-O) at 288.5 eV, and corboxyl (C(=O)OX) at 290.6 eV. The percentage ratio of various carbon chemical species of C 1s was 3.9, 24.1, 45.4, 23.8 and 2.6 corresponding to C=C, C-C/C-H, C-OX, C=O/O-C-O, and C(=O)OX, respectively. Further, the high resolution XPS spectra of rGO for C1s (Figure S6 d) was fitted as hydrocarbon (C=C) at 284.4 eV, (C-C/C-H) at 285.9 eV, (C-OX) at 287.7 eV, (C=O/O-C-O) at 289.0 eV, and (C(=O)OX) at 290.7 eV. The percentage ratio of various carbon chemical species of C 1s was 74.6, 13.3, 4.3, 3.2 and 4.4 corresponding to C=C, C-C/C-H, C-OX, C=O/O-C-O, and C(=O)OX, respectively.
**Figure S6:** (a) Survey scan for XPS spectra of GO, (b) High resolution XPS peaks fitted spectra of C 1s for GO, (c) Survey scan for XPS spectra of rGO, and (d) High resolution XPS peaks fitted spectra of C 1s for rGO.

**Magnetic Property**

**Table S2:** Magnetic parameter for prepared nickel ferrite nanoparticles.

| Sample          | NFD@600 | NFD@800 | NFD@1000 |
|-----------------|---------|---------|----------|
| Magnetic parameter ↓ |         |         |          |
| \( M_s \) (emu/g) | 32.37   | 37.74   | 43.15    |
| \( H_c \) (Oe)   | 63.65   | 93.66   | 9.94     |
| \( M_r \) (emu/g) | 4.07    | 6.13    | 3.00     |
| \( M_r/M_s \)    | 0.125   | 0.162   | 0.069    |
| \( \eta_B \) (\( \mu_B \)) | 1.35    | 1.58    | 1.81     |
| \( K \times 10^3 \) (erg/g) | 2.01    | 3.68    | 0.44     |

**Table S3:** Magnetic parameter for prepared nanocomposites of nickel ferrite nanoparticles and reduced graphene oxide in polypropylene matrix.

| Sample          | NFD@600-rGO-PP | NFD@800-rGO-PP | NFD@1000-rGO-PP |
|-----------------|----------------|----------------|-----------------|
| Magnetic parameter ↓ |               |               |                 |
| \( M_s \) (emu/g) | 19.26          | 22.95          | 25.29           |
| \( H_c \) (Oe)   | 90.56          | 122.93         | 61.37           |
| \( M_r \) (emu/g) | 2.65           | 4.12           | 3.87            |
Dielectric (permittivity) and Electrical Properties (at 1-10^7 Hz) of Nanoparticles

Dielectric and electrical characterization of NiFe_2O_4 nanoparticles at 1-10^7 Hz frequency range were carried out by using Broadband Dielectric Impedance Analyzer Concept 40 system (Novocontrol, Germany) with formation of pellets of these nanoparticles. The real (ε') part of the dielectric constant has been evaluated by using following expression S31:

\[ \varepsilon' = \frac{C \times t}{\varepsilon_oA} \]

where C, A, t and \( \varepsilon_o \) are capacitance in Farad (F), cross-sectional area of the pellet, thickness of pellet, constant for permittivity in free space, respectively. Further, the dielectric loss tangent factor (tanδ) in relation with real part (ε') and imaginary part (ε'') of the dielectric constant can be evaluated by using following relation S32:

\[ \varepsilon'' = \varepsilon' \tan \delta \]

Furthermore, ac electrical conductivity can be evaluated by using following expression S33:

\[ \sigma_{ac} = 2\pi f \varepsilon' \varepsilon_o \tan \delta \]

The frequency dependence of dielectric constant of prepared nanoparticles in the frequency range 1-10^7 Hz is displayed in Figure S7 (a-b). It was noticed that the measured dielectric constant of nanoparticles strongly depends on applied frequency and particle size of nanoparticles. In addition, it can be observed that the dielectric constant abruptly decreases at lower frequency and further at high frequency it becomes constant, which implies dispersion nature of dielectric constant with increase of frequency. The observed dispersion nature in dielectric constant is associated with Maxwell-Wagner’s type of interfacial polarization in

| \( M_r/M_s \) | 0.137 | 0.179 | 0.153 |
|----------------|--------|--------|--------|
agreement with Koop’s phenomenological theory. In view of that the dielectric medium is consisted of good conducting grains and poor conducting grain boundaries. In addition, in spinel ferrite, the polarization follows the similar mechanism as conduction process. The polarization in nickel ferrite is associated with the electron hopping between $\text{Fe}^{2+} \leftrightarrow \text{Fe}^{3+}$ ions and hole hopping between $\text{Ni}^{3+} \leftrightarrow \text{Ni}^{2+}$ ions and consequently charge carriers move to grain boundaries. Because of higher resistance of grain boundaries, the charge carriers pile up there and creates polarization. Further, with the increase of frequency of applied electric field, the charge carriers can’t follow the increased frequency variation, and consequently decrease in polarization. It can be noticed that the dielectric constant of the prepared nanoparticles is increased with decrease of particle size. In smaller sized nickel ferrite nanoparticles, the high value of dielectric constant is due to large surface polarization. Figure (c) depicts the frequency dependence of tangent loss ($\tan \delta$) of the prepared nanoparticles. It can be noticed that the value of tangent loss decreases with increase of frequency and becomes constant at higher frequency. The tangent loss is associated with the polarization lags behind the applied electric field and it is due to grain boundaries and imperfections in the crystals, etc. Further, the tangent loss behaviour is also associated with the domain wall resonance. These losses are noticed to be low at higher frequency, if the domain wall motion is inhibited according to Rezlescu model. Figure (d) presents the frequency dependence variation of ac conductivity of the prepared nanoparticles. Generally, the ac conductivity decreases which is associated with large polaron hopping, however, it increases due to small polaron hopping. Therefore, the observed frequency dependence variation of ac conductivity is associated with small polaron hopping. Further, the increase in ac conductivity is associated with the conduction by electron exchange between the ions of the same element with different valence states. It can be observed from Figure (d) that the ac conductivity increases with decrease of particle size of prepared nanoparticles. The electrical conductivity of the spinel ferrite
depends on the hopping length of the charge carriers. The observed decrease in hopping length with decrease of particle size (Table S1) signifies that the charge carriers need less energy to jump from one cationic site to other, and consequently an increase in ac conductivity.\textsuperscript{S43}

Electric modulus provides another way to investigate the characteristics of electrical conduction in the dielectric material. Figure S7 (e) and Figure S7 (f) display the frequency dependence variation of real part of modulus (M’) and imaginary part of modulus (M’’) of prepared nanoparticles, respectively. The real part of modulus (M’) and imaginary part of the modulus (M’’) can be evaluated by using following relation:\textsuperscript{S44}

\[ M' = \varepsilon'\left[\varepsilon'(\varepsilon')^2 + (\varepsilon'')^2\right] \]
\[ M'' = \varepsilon''\left[\varepsilon'(\varepsilon')^2 + (\varepsilon'')^2\right] \]

It can be observed from Figure S7 (e) that the value of M’ is low at low frequency range and further increases continuously at higher frequency with tendency to saturate due to relaxation process. At low frequency, M’ is approaching to zero, which indicate electronic polarization has negligible value.\textsuperscript{S45} However, at high frequency, M’ increases rapidly, which indicate conduction mechanism is due to short range movement of the charge carriers.\textsuperscript{S46} The broad peak in Figure S7 (f) indicates the existence of relaxation process in the prepared nanoparticles.\textsuperscript{S47} The characteristics frequency at which M’’ is maximum relates to relaxation frequency and consequently its relaxation time. The high frequency side of M’’ peak signifies the range in which the charge carriers are spatially confined to their potential wells and can mobile at short range. However, the low frequency side of M’’ peak signifies the movement of charge carriers over long distances, i.e., possibility of success of hopping of charge carriers. In addition, the peak frequency corresponds to transition from long range to short range mobility with increase of frequency.\textsuperscript{S48} Further, the cole-cole plots between M’ and M’’ for prepared nanoparticles is shown in Figure S7 (g). The cole-cole plot distinguish the role of grain boundaries and grains.
It can be observed from Figure S7 (g) that the cole-cole plot exhibits two semicircles. The grain boundaries have high resistance and low capacitance in comparison with grains, consequently, the resistance of grain boundaries resulted to semicircle at smaller frequency, however high frequency semicircles correspond the results from the grains.\textsuperscript{849}
Figure S7: (a) Real part of dielectric constant, (b) Imaginary part of dielectric constant, (c) dielectric loss, (d) ac conductivity, (e) real part of modulus M’, (f) imaginary part of modulus M’’, (g) cole-cole plots, for NiFe$_2$O$_4$ nanoparticles

Theoretical Electromagnetic Interference Shielding

When electromagnetic wave incident on shielding nanocomposite, the incident power is divided into transmitted power ($P_T$), absorbed power ($P_A$) and reflected power ($P_R$). The corresponding coefficients of transmissivity ($T$), absorptivity ($A$), and reflectivity ($R$) follows the following relation $^8$:

$$1 = R + A + T$$

Further, the reflectivity ($R$) and transmissivity ($T$) have following relation with scattering parameters such as $S_{11}$, $S_{22}$, $S_{21}$ and $S_{12}$ $^9$:

$$R = |S_{11}|^2 = |S_{22}|^2$$

$$T = |S_{21}|^2 = |S_{12}|^2$$

The total EMI shielding effectiveness ($SE_T$) is the contribution of absorption loss ($SE_A$), reflection loss ($SE_R$) and multiple reflection ($SE_M$) $^8$:

$$SE_T(dB) = SE_R + SE_A + SE_M$$

where $SE_M$ can be negligible when $SE_T$ is higher than 10 dB $^9$.

In terms of scattering parameters and R, T and A, the EMI shielding effectiveness ($SE$) is given by following relation $^8$:

$$SE_T(dB) = -10 \log (T) = -10 \log (|S_{21}|^2)$$
\[
SE_R(dB) = -10 \log (1 - R) = -10 \log \left(1 - |S_{11}|^2\right)
\]

\[
SE_A(dB) = -10 \log \left(\frac{T}{1 - R}\right) = -10 \log \left(\frac{|S_{21}|^2}{1 - |S_{11}|^2}\right)
\]

The shielding effectiveness through reflection (SE\textsubscript{R}) depend on the total conductivity and the relative permeability of the shielding material by following relation \textsuperscript{555}:

\[
SE_R = -10 \log \left(\frac{\sigma_T}{16 \omega \varepsilon_0 \mu_r}\right)
\]

where \(\sigma_T\) is the total conductivity, and \(\mu_r\) is the relative permeability. From this above relation, it is clear that the SE\textsubscript{R} depends on the ratio of the electrical conductivity and relative permeability of the shielding material. The shielding effectiveness through absorption (SE\textsubscript{A}) has following relation in terms of the electrical conductivity and permeability of the shielding nanocomposite \textsuperscript{556}:

\[
SE_A = -8.68 t \left(\frac{\sigma_T \omega \mu_r}{2}\right)^{1/2}
\]

where \(t\) is the thickness of the shielding material. It is clear from this above relation that the SE\textsubscript{A} depends on the product of the electrical conductivity and permeability of the shielding material.

**Mechanical Properties of Nanocomposites**

| Samples          | Young’s Modulus (MPa) | Tensile Strength (MPa) | Elongation at break (%) |
|------------------|-----------------------|------------------------|-------------------------|
| NFD@600-rGO-PP   | 33.34 ±2.15           | 1.89 ±0.08              | 24.01 ±2.02             |
| NFD@800-rGO-PP   | 28.19 ±0.74           | 2.21 ±0.08              | 77.38 ±1.98             |
Table S4: Tensile properties of prepared nanocomposites

|     | Tensile Strength (MPa) | Young's Modulus (GPa) | Elongation (%) |
|-----|------------------------|-----------------------|----------------|
| NFD@1000-rGO-PP | 24.55 ±2.08            | 2.36 ±0.22            | 259.34 ±2.28   |

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