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Article

Hybrid Magneto-Responsive Composites Made from Recyclable Components: Tunable Electrical Properties Under Magnetic and Mechanical Fields

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Abstract: This study presents the fabrication and characterization of hybrid magneto-responsive composites (hMRCs), which are composed entirely of recyclable components: magnetite microparticles (MMPs) as fillers, lard as a natural binding matrix, and cotton fabric for structural reinforcement. MMPs are obtained by in-house plasma-synthesis, a sustainable, efficient, and highly tunable method for producing high-performance MMPs. The resulting hMRCs are integrated into flat capacitors, and their electrical capacitance (C), resistance (R), dielectric permittivity (ϵ') and electrical conductivity (σ) are investigated under a static magnetic field, uniform force field and an alternating electric field. The experimental results reveal that the electrical properties of hMRCs are dependent on the volume fractions of MMPs and microfibers in the fabric, as well as the applied magnetic flux density (B) and compression forces (F). C shows an increase with both B and F , while R decreases due to improved conductive pathways formed by alignment of MMPs. σ is found to be highly tunable, with increases of up to 450 % under combined field effects. In the same conditions, C increases up to 60 %, and R decreases up to 80 %. Thus, by employing plasma-synthesized MMPs, and commercially available recyclable lard and cotton fabrics, this study demonstrates an eco-friendly, low-cost approach to designing multifunctional smart materials. The tunable electrical properties of hMRCs open new possibilities for adaptive sensors, energy storage devices, and magnetoelectric transducers.

Keywords: hybrid magneto-responsive composites; plasma-synthesized magnetite microparticles; recyclable functional materials; tunable electrical properties; smart materials for sensing

1. Introduction

The increasing demand for smart multifunctional materials with adaptable physical properties has driven intense research in sensor technologies, flexible electronics and adaptive energy storage systems [1–4]. Among these, magneto-responsive materials are particularly promising due to their ability to modify mechanical and electrical properties in response to external stimuli, offering diverse applications in biomedical sensors [5], soft robotics [6], and active rheology control of cementitious materials [7].

Conventional magnetorheological (MR) suspensions [8–12] and electrorheological (ER) fluids [13–15] have been widely investigated for their field-dependent behavior. Despite significant advancements in field-responsive materials, several critical challenges remain in designing materials that *simultaneously* achieve mechanical adaptability, electrical tunability, and environmental sustainability.

Traditional MR and ER suspensions are inherently fluid-based, which introduces issues related to long-term stability, sedimentation, and the need for specialized containment systems [16–18]. These factors significantly limit their deployment in wearable electronics, flexible devices, and smart mechanical systems, where sustained performance over extended periods is essential. Furthermore, existing MR and ER materials typically respond to either magnetic or electric fields [19–22], with few exceptions in successfully combining both multi-field responsiveness and structural stability within a single material system [23–27].

Additionally, recyclability and sustainability remain overlooked aspects in the design of these materials. Most formulations rely on synthetic polymers and complex chemical binders, leading to environmental concerns regarding disposal and long-term ecological impact. The embedded microparticles, which determine the suspension's responsiveness to external fields, are often produced through either chemical [28,29] or physico-chemical synthesis methods [30,31]. Chemical synthesis, although capable of creating dual-functional microparticles, is often hindered by the use of complex processes and environmentally hazardous reagents. Consequently, there has been a shift toward more sustainable alternatives, such as plasma-based physical synthesis [32–35] or green synthesis using waste natural materials [36,37]. These methods provide a scalable and eco-friendly approach for producing magnetite microparticles (MMPs) from recyclable materials, including onion, potato, tea, maringa and gaharu leaves, or carbon steel waste rods.

This study aims to overcome the environmental and technological challenges associated with traditional particle synthesis methods by developing multifunctional, stable and low-cost hybrid magneto-responsive composites (hMRCs) composed entirely of recyclable components. MMPs are synthesized through a plasma-based process that recycles carbon steel rods [38] used in civil constructions, reducing material waste and environmental impact. The composites use lard and cotton fabric as the matrix materials, both of which are commercially available and recyclable. Lard provides a stable, hydrophobic medium that reduces particle sedimentation and agglomeration due to its high viscosity and natural fat composition [39]. Its semi-solid state ensures even distribution of MMPs. When the mixture of lard and MMPs is soaked into cotton fabric, the MMPs are uniformly absorbed, creating magnetically responsive textiles with potential applications in wearable sensors, electromagnetic shielding, and protective gear. The lard also temporarily binds the particles to the fibers, enhancing particle adhesion and enabling further functionalization.

The primary objective is to investigate how these hMRCs respond to static magnetic fields and uniform compression, particularly in terms of their dielectric and electrical properties. The study also seeks to demonstrate the application of these hybrid materials in smart capacitors, evaluating their potential as field-responsive mechanical deformation sensors with adjustable sensitivity. By exploring the relationship between material composition, external fields, and electrical behavior, this work contributes to the development of sustainable, multifunctional materials for adaptive devices. These findings have potential applications in automotive sensors, wearable electronics, soft robotics, and energy storage systems, where tunable material properties are essential for performance optimization.

The remainder of this paper is organized as follows. Section 2 describes the materials and methods used to synthesize and characterize the hMRCs. Section 3 details the experimental results, focusing on the electrical properties of the fabricated capacitors and their responses to varying magnetic and mechanical field conditions. Section 4 presents an in-depth discussion of the results, emphasizing the physical mechanisms governing field-induced property changes. Finally, Conclusions section provides a summary of the key findings and their implications for future applications in smart and adaptive materials.

2. Materials and Methods

2.1. Materials

For the fabrication of hMRCs, the following materials are used: MMPs (see details in Appendix A), lard (from Elit, Alba Iulia, Romania) and cotton fabric.

The electrical properties of MMPs, lard and fabric are measured at a temperature of 24 °C using the flat capacitor (FC) method [25]. The results are summarized in Table 1 and show that all electrical properties are dependent on the nature of the materials used. This dependency arises from the formation of conductive nano-micro layers [23] by MMPs, between which oxides act as dielectric materials. These networks of microcapacitors result in an equivalent capacitance (C) and ϵ' up to 2.58 times higher than that of lard.

Table 1. C , dielectric loss coefficient (D), relative dielectric permittivity (ϵ'), dielectric loss factor (ϵ'') and mass density ρ of MMPs, lard and cotton fabric.

Component	C , (pF)	D	ϵ'	ϵ''	ρ (g/cm ³)
MMPs	45.50	0.1007	16.4255	1.6540	3.388
Lard	17.65	0.0209	6.3717	0.1332	0.885
Cotton fabric	19.22	0.1783	1.4473	0.2581	-

Table 2. Volumes, volume fractions, masses and mass fractions of lard (L) and MMPs (P).

V_L (cm ³)	V_P (cm ³)	Φ_L^V (% vol.)	Φ_P^V (% vol.)	m_L (g)	m_P (g)	Φ_L^m (% vol.)	Φ_P^m (% vol.)
6	4	60	40	6.126	7.772	$\simeq 44$	$\simeq 56$

However, the value of ϵ' for the cotton fabric is much lower compared to that of MMPs and lard. The difference is due to the presence of air in the empty spaces between the fibers of the fabric. The table also shows that the ϵ'' of MMPs is approximately one order of magnitude higher than the values for both lard and cotton fabric. In the later case, the value of ϵ'' is determined by the moisture present in the cotton microfibers.

2.2. Preparation of MMPs + lard Mixture and hMRCs

The specified quantities of MMPs and lard listed in Table 2 are introduced in a Berzelius cylinder. and a mixture is obtained (Figure 1a). Then, the mixture is homogenized at 220 – 250°C for 500 s, followed by cooling to room temperature.

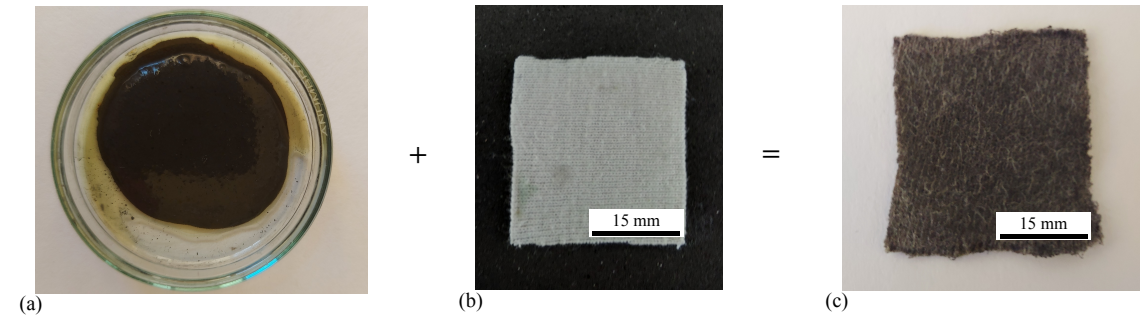


Figure 1. Preparation of hMRCs. (a) MMPs + lard mixture. (b) Cotton fabric. (c) hMRC.

Table 3. Volumes, volume fractions of lard, MMPs, and microfibers f used in preparation of hMRC₁ and hMRC₂. σ - saturation magnetization.

	V_L (cm ³)	V_P (cm ³)	V_f (cm ³)	Φ_L (% vol.)	Φ_P (% vol.)	Φ_f (% vol.)	σ ($\frac{Am^2}{Kg}$)
hMRC ₁	0.20	0.14	0.14	42	29	29	9.68
hMRC ₂	0.31	0.28	0.14	42	39	19	13.12

Afterwards, two identical cotton fabric pieces are cut at dimensions 30 mm $\times$ 30 mm $\times$ 0.6 mm (Figure 1b) and then soaked in MMPs + lard mixture to create hMRCs samples (Figure 1c), denoted hMRC₁ and hMRC₂. Volumes and volume fractions of these components are provided in Table 3.

2.3. Structural Properties of hMRCs

The crystalline structure, phase and morphology of hMRC₁ and hMRC₂ are studied using XRD and SEM techniques. XRD analysis confirmed the cubic magnetite phase in both hMRC₁ and hMRC₂ (Figure 2a). Differences in peak intensities suggest variations in crystallite size and phase interactions. SEM data (Figure 2b) show the presence of MMPs with dimensions ranging from few micrometers up to few hundred micrometers stuck to the cotton microfibers. This is facilitated by the presence of lard, which covers MMPs (Appendix B).

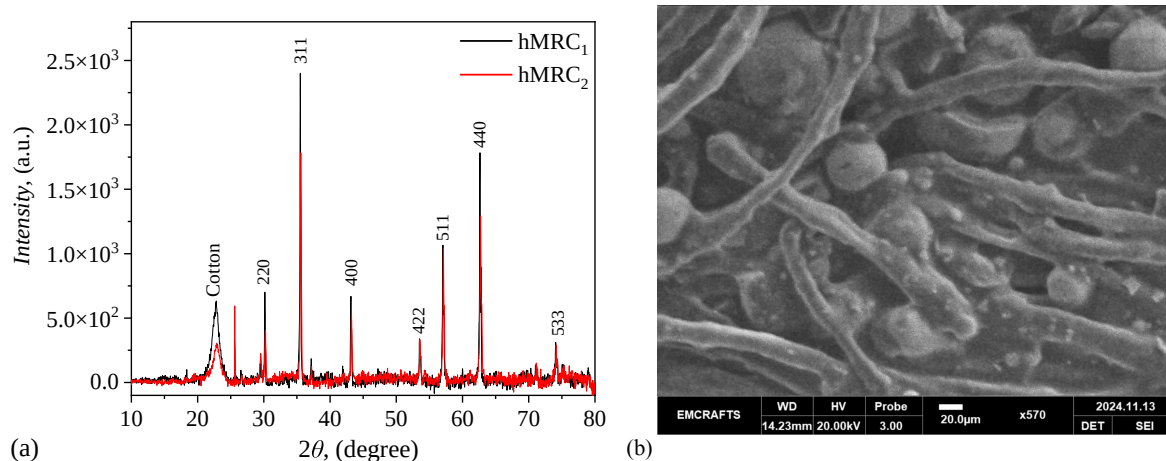


Figure 2. (a) XRD diffraction from hMRC₁ and hMRC₂. (b) SEM from hMRC₁. Spherical structures - MMPs; Elongated structures - cotton microfibers.

2.4. Magnetic Properties of hMRCs

The magnetization curves (Figure 3) are obtained by using an experimental setup described in Ref. [40]. The MMPs + lard mixture, which lacks the cotton matrix, displays magnetization levels between those of the hMRCs and MMPs. The lower magnetization of hMRCs (vs. MMPs) is due to the cotton matrix reducing particle alignment.

These magnetization properties play a critical role in the practical applications of hMRCs. For instance, the ability to adjust magnetization through matrix composition and magnetite content allows for tuning the sensitivity and responsiveness of mechanical sensors, such as strain or deformation sensors. The reduced coupling in fabric-embedded suspensions enhances stability under varying mechanical conditions, making them suitable for field-responsive materials in applications where precise control of rheological and magneto-mechanical behavior.

2.5. Manufacturing of FC

The manufacturing of FC is carried out using a strati-textolite (STP) with a thickness of 0.6 mm, WR-Type 611 (from Rademacher, Germania) and hMRCs. On one side of STP there is a thin copper layer. From the STP board, four pieces are cut, each one with dimensions 30 mm × 30 mm (Figure 4a). On each STP, two electrical conductors are welded with tin-lead alloy. FC₁ and FC₂ are fabricated by sandwiching hMRC₁, and respectively hMRC₂ between the copper-coated plates (Figure 4b), with insulation tape applied (Figure 4c). Appendix C provides additional details on the components of FC.

2.6. Experimental Setup for Measuring the Electrical Properties of FC

The setup depicted in Figure 5 comprises an electromagnet, between the poles of which FCs are alternately inserted. The electromagnet is powered by a DC source (model RXN-3020D, manufactured by HAOXIN, China). The magnetic flux density B between the north (N) and south (S) poles is regulated by adjusting the electric current supplied to the electromagnet coil (pos. 2) through the DC source. A Hall probe (h; Gaussmeter DX-102, model DX-102, from DexingMagnet, China) was

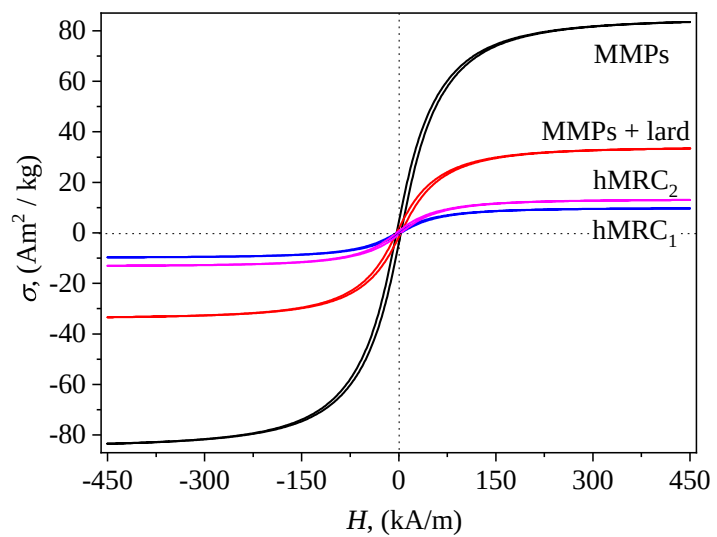


Figure 3. Relative saturation magnetization for hMRC₁ and hMRC₂, together with those of MMPs and MMPs + lard (for reference).

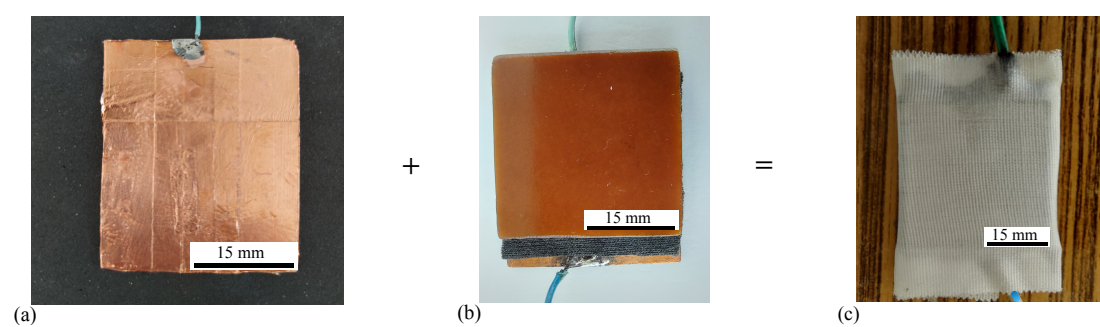


Figure 4. Manufacturing of FC. (a) One STP welded with a conductor (top). (b) Two STPs with hMRC (black) between them. Each STP are welded with a conductor. (c) The resulting FC, covered with a self-adhesive insulating tape (white-gray).

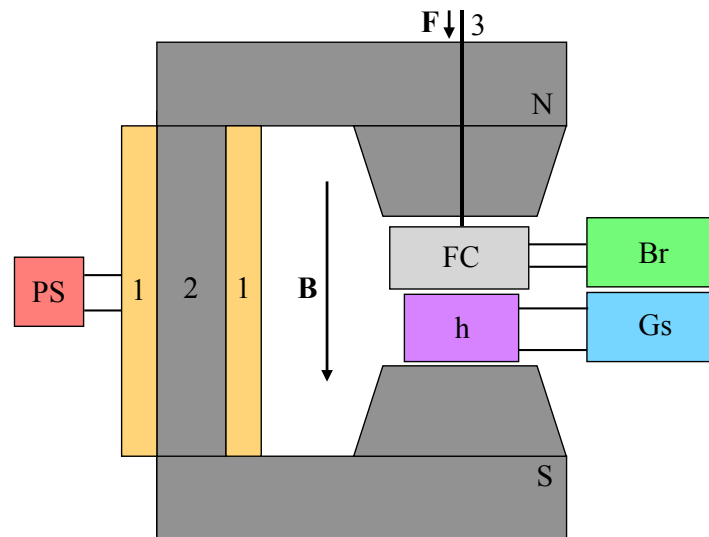


Figure 5. Experimental setup (overall configuration) for measuring properties of FC: 1 - coil, 2 - magnetic yoke, 3 - non-magnetic shaft, N and S, magnetic poles, PS - DC power supply, Br - RLC bridge, Gs - gaussmeter, FC - flat capacitor, h - Hall probe, B - magnetic flux density vector, F uniform compressive force.

used to measure B . The capacitors and h , are secured by mechanical tensioning. This is achieved using a non-magnetic platform (not shown in Figure 5) and a non-magnetic shaft (pos. 3 in Figure 5). The mechanical tension exerted by the non-magnetic body on the surface of the capacitors is due to compression forces, which are increased in steps of 0.5 N within the interval from 0 to 3 N.

C and equivalent resistance (R) are measured using an RLC bridge Br (model CHY-41R, made in Taiwan). These measurements are taken while the capacitors are subjected to an alternating electric field of frequency $f = 1$ kHz, superimposed with a magnetic field and uniformly applied compression forces F . The measured values are recorded after stabilization, i.e. after a time interval $t = 20$ s following the application of B and F on the capacitors.

3. Electrical Properties of FC

The measurements of electrical properties are performed under the same conditions as those used for MMPs and lard, described in the Appendix D.

3.1. Electrical Capacitance and Resistance

C and R are measured in a static magnetic field superimposed on the static compressive force field. The static magnetic field is increased with a step of 10 mT, up to the maximum value of 150 mT. The variation of capacitance with B for different values of F , i.e. the function $C = C(B)_F$, is shown in Figure 6. Similarly, resistance $R = R(B)_F$, is shown in Figure 7.

The capacitance measurements reveal a clear dependence on both B and F . For the former case, the dependence is quasi-linear. For FC_1 , at $B = 0$ mT, C increases from 79 pF with no force to 94 pF when $F = 3$ N. At $B = 150$ mT, the capacitance rises to 97.2 pF without force and reaches 113 pF at $F = 3$ N. Similarly, for FC_2 , C starts at 103 pF with $F = 0$ N and $B = 0$ mT, increasing to 135 pF at $F = 3$ N. At 150 mT, C ranges from 139 pF ($F = 0$ N) to 178 pF ($F = 3$ N). This demonstrates a higher overall capacitance and sensitivity for FC_2 due to its increased magnetite content.

The combined effects of B and F enhance polarization within the suspensions. These changes suggest that by tuning the magnetic and mechanical parameters, the dielectric response of the capacitors can be precisely controlled. This tunability is advantageous for mechanical deformation sensors, where sensitivity to small force changes is critical. For instance, in FC_2 , the capacitance increases by approximately 30 % with the application of a 3 N force at $B = 0$ mT, compared to about 19 % in FC_1 .

The resistance measurements for the capacitors demonstrate a strong dependence on both B and applied compression force. Resistance decreases quasi-linearly with increasing magnetic field for both

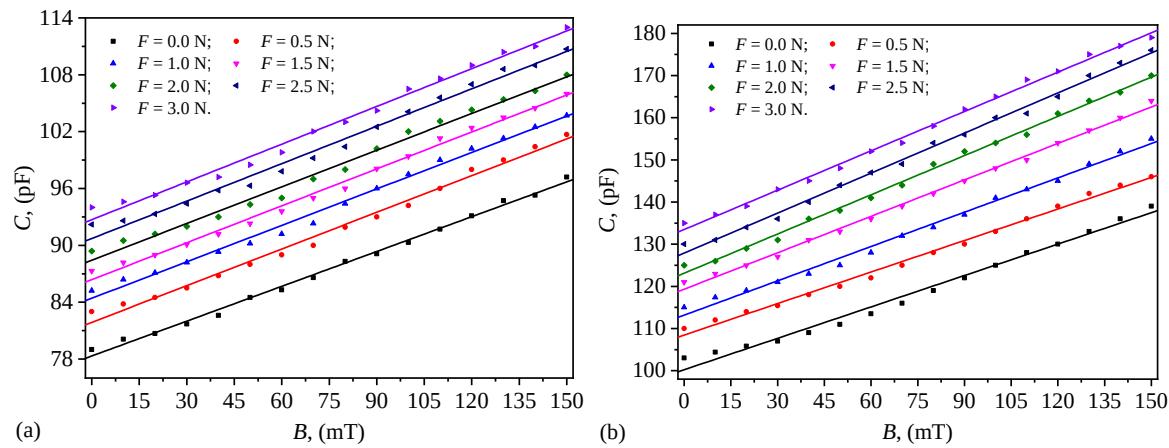


Figure 6. The capacitance as a function of B , for fixed values of F . (a) FC_1 . (b) FC_2 .

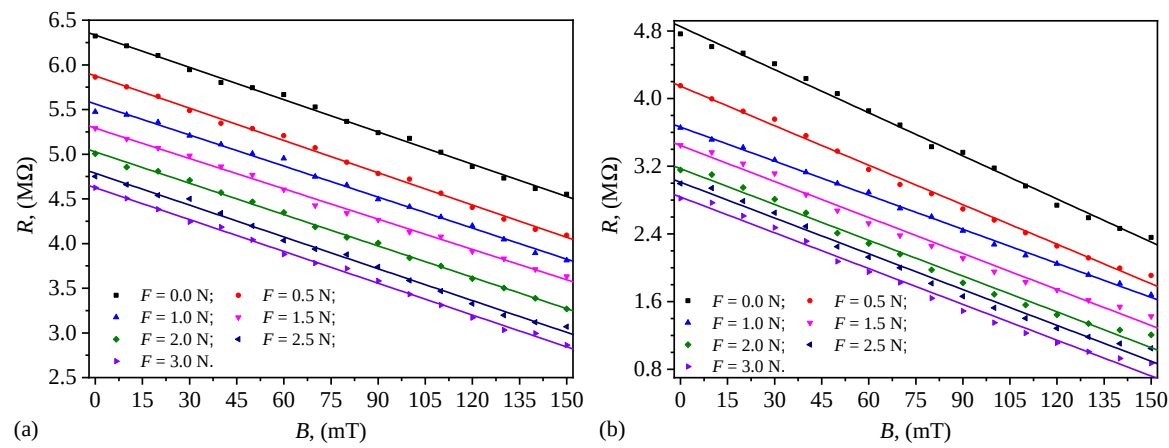


Figure 7. R as a function of B , for fixed values of F . (a) FC_1 . (b) FC_2 .

suspensions, indicating that the alignment of magnetite particles under the magnetic field enhances conductive pathways within the hybrid matrix. This effect is further amplified by compression forces, which improve particle contact and reduce insulating voids within the structure. For example, in FC₁, R drops from 6.321 M Ω at $B = 0$ mT and $F = 0$ N to 4.625 M Ω at $F = 3$ N. Similarly, in FC₂, R decreases from 4.764 M Ω to 2.82 M Ω under the same conditions.

Comparing the two capacitors, FC₂ exhibits lower resistance across all field conditions due to the higher volume fraction of magnetite in hMRC₂. The increased concentration of conductive particles reduces the effective resistivity of the material by enhancing the density of current pathways. This behavior also suggests that FC₂ is more responsive to both mechanical and magnetic field inputs, as the conductive network becomes more stable and efficient under combined field conditions.

3.2. Relative Dielectric Permittivity

From the formula of the parallel-plate capacitor, the relative dielectric permittivity ϵ' is obtained as $\epsilon' = h_0 CS / \epsilon_0$, where h_0 is the distance between the plates of the capacitor, $\epsilon_0 = 8.854$ pF/m is the vacuum permittivity, and S is the area of the common surface of the plates of the capacitor. For the FC with MMPs and lard the numerical values used here are $h_0 = 2 \times 10^{-3}$ m and $S = 6.25 \times 10^{-4}$ m². Thus, ϵ' can be written as:

$$\epsilon' \simeq 0.361 \text{ pF}^{-1} \times C(\text{pF}). \quad (1)$$

For MMPs, lard, and cotton fabric, they are quasi-constant, and the values are reported in Table 1 (together with the dielectric loss factor ϵ'').

For the capacitors with cotton fabric we have $h_0 = 6 \times 10^{-4}$ m and $S = 9 \times 10^{-4}$ m², and thus:

$$\epsilon' \simeq 0.0753 \text{ pF}^{-1} \times C(\text{pF}). \quad (2)$$

This shows that for the capacitors used, ϵ' has identical shapes, with values shifted vertically downward by the corresponding coefficient. Thus, they also increase with both B and applied F due to enhanced polarization. These results indicate that magnetic and mechanical fields strongly influence the dielectric response of the suspensions.

3.3. Electrical Conductivity

Taking into account the expression of electrical conductivity (σ) of a linear resistor, for hMRCs obtained here, it can be written as:

$$\sigma = h_0 / (RS). \quad (3)$$

Using the same numerical values as in Section 3.1, Equation (3) becomes:

$$\sigma = 0.67(m^{-1}) / R(\text{M}\Omega) \quad (4)$$

The results are plotted in Figure 8 and show that σ has a strong dependence on both B and F . σ increases with B due to improved alignment of magnetite particles. As above, compression forces further augment this effect by reducing insulating voids and increasing particle-particle contact efficiency, thereby improving the overall conductivity.

A comparison between FC₁ and FC₂ highlights the impact of material composition on electrical properties. FC₂, with a higher MMPs content, exhibits significantly greater conductivity than FC₁ across all field conditions.

3.4. Quantification of the Contribution of Magnetic and Compression Fields on C , R , and σ

The effects of magnetic and compression field on C , R and σ of hMRCs are quantified by the relation:

$$\alpha = \left(\frac{\Lambda(B)_F}{\Lambda_0} - 1 \right) \times 100, \quad (5)$$

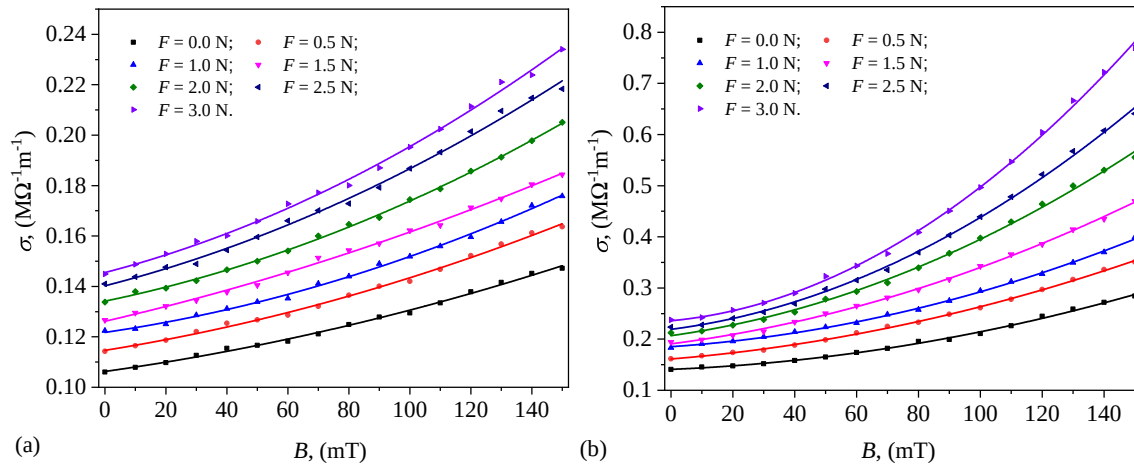


Figure 8. σ as a function of B , for fixed values of F . (a) FC₁. (b) FC₂.

where Λ is $C(B)_F$, $R(B)_F$ or $\sigma(B)_F$ from Figures 6, 7 and 8, and Λ_0 are the corresponding value when neither magnetic nor compression fields are applied.

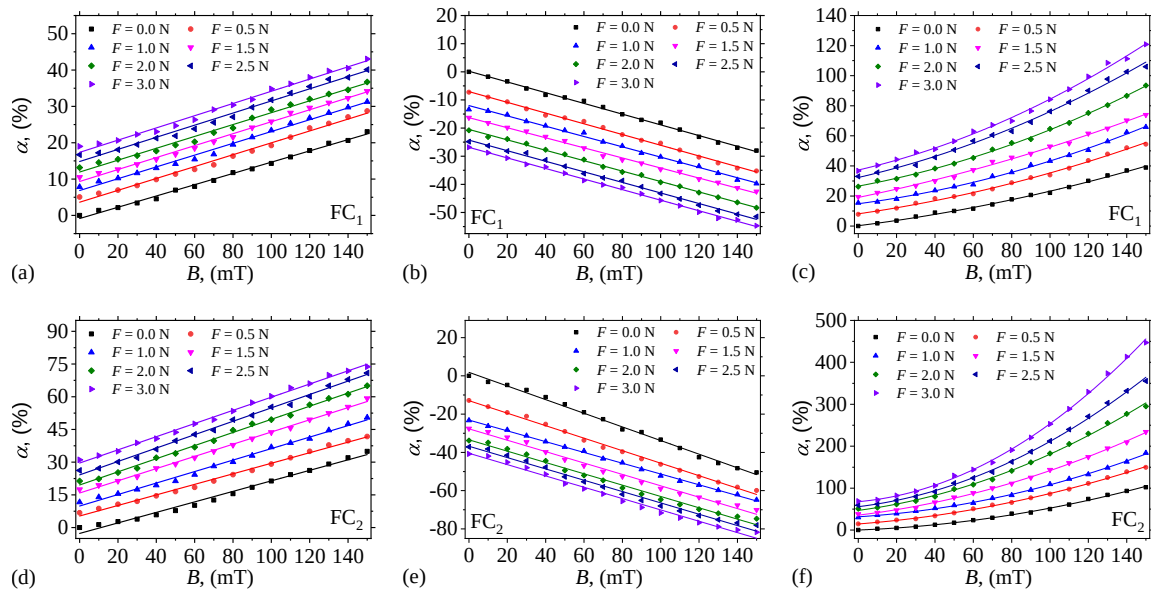


Figure 9. Variation of α (Equation 5) with B , for fixed values of F . (a) and (d) Quantification of C for FC₁, and respectively FC₂. (b) and (e) Quantification of R for FC₁, and respectively FC₂. (c) and (f) Quantification of σ for FC₁, and respectively FC₂.

The quantification of the capacitance increase in capacitors FC₁ (Figure 9a) and FC₂ (Figure 9d) highlights the influence of both B and F . As the magnetic and compression fields increase, the C rises significantly, indicating enhanced polarization within the dielectric medium. FC₂, with a higher magnetite content, shows a more pronounced increase in C compared to FC₁.

The quantification of the resistance reduction for capacitors FC₁ (Figure 9b) and FC₂ (Figure 9e) complements the capacitance analysis, highlighting the influence of both B and F on σ . For example, at $B = 0$ mT and $F = 3$ N, FC₁ shows a resistance reduction of approximately 27 %, while FC₂ exhibits a more substantial reduction of over 40 %. At higher B (e.g., 150 mT), the reductions reach 54.7 % and 81.7 % for FC₁ and FC₂, respectively. These reductions correspond to σ increases of around 120 % for FC₁ (Figure 9c) and nearly 450 % for FC₂ (Figure 9f), highlighting the significant impact of the combined magnetic and mechanical fields on enhancing material conductivity. Unlike conventional MR suspensions, which exhibit little to no change in electrical properties under a magnetic field, these

changes indicate that hMRCs can function as a field-responsive dielectric material, where both charge distribution and conductive pathways are modulated by external magnetic and mechanical stimuli.

These observations correlate with the capacitance data, where both polarization and conductivity improve under field-induced particle alignment and compression. The higher MMPs content in hMRC₂ results in a more pronounced reduction in resistance, consistent with its larger capacitance increase under similar conditions.

4. Discussions

4.1. Scalability and Process Optimization of Plasma-Synthesized MMPs

The feasibility of scaling up plasma-based synthesis is a crucial consideration for industrial adoption [38,41]. The method used in this study, which involves plasma arc pulverization of carbon steel rods [38], offers several advantages over conventional chemical synthesis routes, particularly in terms of sustainability and material recycling. One of the major advantages is its ability to instantaneously generate high-purity MMPs from waste materials without the need for extensive purification steps. This is particularly beneficial in industrial applications where large-scale production of magnetically responsive materials is required, such as in adaptive sensors, flexible electronics, and magnetoelectric transducers [42]. However, compared to conventional chemical precipitation or sol-gel methods, the plasma process requires a high initial energy input [43] to maintain the plasma arc, which could be a limiting factor for widespread commercial use.

Thus, to enhance scalability and process efficiency, alternative synthesis environments can be considered. One approach involves obtaining microparticles in an inert environment, such as argon, which prevents unwanted oxidation but does not actively reduce Fe³⁺ species. A more effective method could involve using a mixture of argon with reducing gases such as hydrogen or ammonia, which would help protect the MMPs from oxidation and stabilize the magnetite phase. Additionally, collection of microparticles in protective liquid matrices, such as mineral oils combined with inert or reducing gas environments, could further prevent oxidation and allow for immediate integration into liquid-based magnetorheological fluids or suspensions. These modifications could significantly improve the efficiency of plasma synthesis while maintaining high product quality, making the technique more viable for industrial applications.

The integration of these protective environments into the plasma-based synthesis process can improve the stability and yield of MMPs while simultaneously enhancing the scalability of the technique. By further optimizing plasma arc parameters, such as discharge current and feed rate, it may be possible to reduce energy consumption while maintaining high production yields. The adaptability of the plasma approach to different gas environments and collection methods underscores its potential as a scalable and sustainable alternative to traditional magnetite synthesis techniques.

4.2. Comparison with Conventional ER/MR materials

A significant advantage of hMRCs over traditional MR and ER suspensions is their ability to simultaneously respond to both magnetic and mechanical fields while maintaining structural stability. Conventional MR and ER fluids are widely used in adaptive damping systems, vibration control devices, and active rheology applications, where an external magnetic or electric field induces viscosity changes. However, these suspensions typically face two major challenges: (i) sedimentation instability due to density mismatches between the magnetic/dielectric particles and the carrier fluid, and (ii) limited tunability in response to external fields [44]. MR fluids, for instance, are primarily responsive to magnetic fields, whereas ER fluids require high external voltages (often exceeding 3 kV/mm), making them energy-intensive and less practical for certain applications.

In contrast, the hMRCs obtained here offer improved structural stability due to their solid-state composition, where MMPs are embedded within a natural lard matrix and reinforced with cotton fabric. This design mitigates sedimentation issues commonly associated with MR suspensions and eliminates the need for specialized containment systems. Furthermore, the ability of hMRCs to

modulate their electrical properties (capacitance, resistance, and conductivity) under simultaneous magnetic and mechanical stimuli distinguishes them from conventional MR/ER materials, which typically exhibit limited electrical property variations under field exposure. The strong increase in conductivity (up to 450 %) and capacitance (up to 60 %) under external fields suggests that hMRCs could be a viable alternative for adaptive electronic components, where field-controlled electrical properties are required.

The 450 % increase in electrical conductivity observed in the hMRCs can be attributed to a complex interplay of microstructural and electronic effects. A primary mechanism involves the field-induced alignment of MMPs, which enhances percolation pathways for charge transport. Under an applied magnetic field, dipolar interactions between MMPs facilitate their reorientation and chaining along field lines, reducing interparticle distances and forming more efficient conductive paths. This effect is further amplified by mechanical compression, which reduces air gaps and contact resistance between particles, allowing for improved charge transfer. Additionally, the soft, viscoelastic nature of the lard matrix enables localized deformation under pressure, leading to better interfacial connectivity between conductive particles.

Beyond structural reorganization, several electronic transport mechanisms also contribute to the conductivity enhancement. Field-controlled dielectric breakdown within the lard matrix may occur, wherein applied fields induce polarization of molecular components, reducing resistivity in localized regions. Furthermore, magnetostriction-induced microstructural rearrangements may lead to dynamic changes in particle distribution, enhancing connectivity. In nanoscale junctions, quantum tunneling effects could also play a role, particularly under strong compression, where the narrowing of insulating barriers facilitates electron transport. The combination of these factors, i.e. particle alignment, contact resistance suppression, dielectric modifications, and tunneling contributions, explains the highly tunable electrical response of hMRCs, making them a promising class of materials for adaptive electronic components and magnetoelectric applications.

From an application perspective, the ability of hMRCs to function as mechanical deformation sensors, tunable capacitors, and adaptive resistors expands their potential use beyond traditional MR/ER applications. While MR suspensions are mainly limited to mechanical damping and actuation, and ER suspensions require high electric fields, hMRCs provide a field-controlled tunable dielectric response, making them suitable for magnetoelectric transducers, wearable electronics, and electromagnetic shielding. These multifunctional properties place hMRCs in a unique category of smart materials that bridge the gap between MR/ER fluids and solid-state adaptive electronic materials.

4.3. Future Directions for Large-Scale Implementations

To bridge also the gap between laboratory-scale development and industrial application, future research should focus on refining the plasma-based synthesis method to further enhance its industrial scalability. This includes optimizing the plasma arc parameters to reduce energy consumption while maintaining high production yields and investigating alternative methods for controlling particle size distribution. The incorporation of protective environments should be systematically studied to determine their effects on particle stability and magnetic properties. Additionally, long-term mechanical and electrical stability testing under real-world conditions will be necessary to validate the practical applicability of these materials in commercial devices.

By addressing these challenges, plasma-based synthesis could become a key enabling technology for the large-scale production of advanced magneto-responsive composites. Further collaborations with industrial partners will be essential to optimize manufacturing conditions and to explore integration strategies for these composites in existing production lines. The potential for waste material utilization and sustainable material design makes this approach highly relevant for industries seeking eco-friendly solutions for high-performance functional materials.

Conclusions

This study successfully developed hMRCs using recyclable cotton fabric, lard, and MMPs synthesized from recycled carbon steel rods through an argon plasma process. The electrical properties of these hybrid composites are systematically investigated using capacitors subjected to an alternating electric field ($f = 1$ kHz), a static magnetic field, and uniform compression forces.

The experimental results demonstrate that the relative dielectric permittivity and electrical conductivity of hMRCs can be effectively controlled by adjusting the volume fraction of MMPs. Additionally, the application of static magnetic fields and compressive forces significantly influences the capacitive and resistive responses of the capacitors. The findings indicate that these devices can function as mechanical sensors with tunable sensitivity, where the degree of mechanical deformation detection can be modulated via an external magnetic field.

Furthermore, the ability to fine-tune dielectric permittivity and electrical conductivity at low compression forces highlights the potential of these materials for applications in adaptive sensing, energy storage, and magnetoelectric transducers. By employing sustainable and low-cost materials, this work contributes to the development of environmentally friendly multifunctional materials. Future work will focus on scaling up production and integrating hMRCs into real-world devices for industrial testing and commercialization.

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Appendix A. Setup for Producing MMPs

The setups for generation of the argon plasma jet (ArPJ) and argon plasma arc (ArPA) have the configuration shown in Figure A1(a), and respectively in Figure A1(b). They include the plasma generator (PG), the argon supply and flow regulation system (APF), the direct current power source (PS), and a system for positioning and adjusting the rod feed rate in the plasma (SPARP). The PG generator includes the thoriated tungsten electrode (TTE) and the water-cooled nozzle (NZ).

The APF system includes an argon cylinder, bottled at a pressure of 150 bar, equipped with a pressure regulator and a flowmeter. The PS source has a no-load voltage of $260 V_{dc}$ and a falling volt-ampere characteristic. The SPARP system allows for up-down adjustment of the position of the PG relative to an electrode rod (ERod), made of carbon steel, as well as continuous adjustment of the rod feed speed v_f into the plasma.

To obtain the MMPs, the following steps are performed. The argon flow rate is adjusted to specific values. The plasma jet is ignited by connecting the PS source to the PG generator and applying a high-frequency voltage between the TTE and NZ electrodes. This results in the formation of the ArPJ (Figure A2 - Left panel), sustained by a current whose intensity is limited by a resistor. At the moment ArPJ forms, the contact K opens, transferring the ArPA to the ERod. At that point, the ERod begins linear motion at pre-set speeds v_f . Instantly, the ERod is transformed into metal vapor carried by the ArPJ (Figure A2 - Left panel). The plasma is generated at a discharge current of intensity $100 \leq I(A_{dc}) \leq 350$. This corresponds to a power density ranging between 945 and 2422 mW/m².

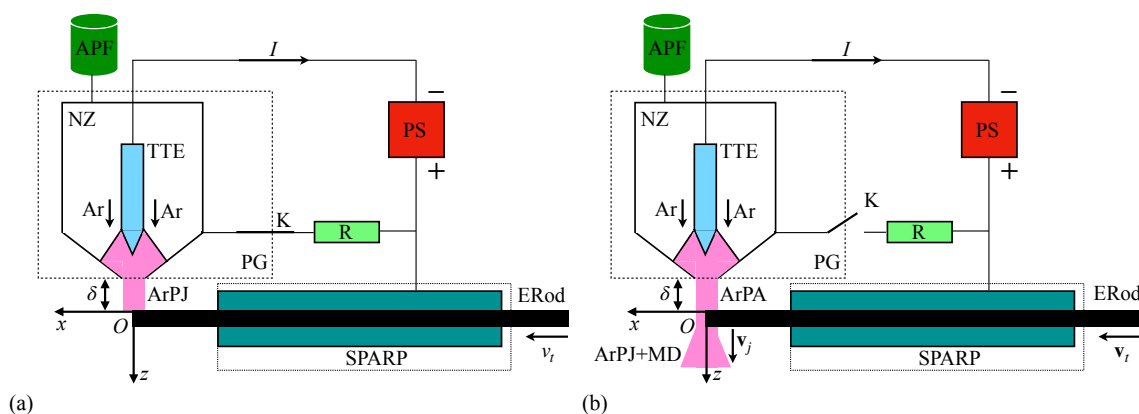


Figure A1. (a) Schematic representation of the experimental setup for obtaining MMPs. (a) Generation of ArPJ. (b) Generation of ArPA. APF - argon cylinder under pressure, NZ - nozzle, TTE - thorium tungsten electrode, Ar - Argon, K - electric contactor, PS - DC power supply, R - electric current limiting resistor, PG - plasma generator with TTE and NZ, δ - nozzle-to-rod distance, MD - metal droplets, ERod - the rod, SPARP - system for positioning and advancing the rod into the plasma, v_t - velocity of ER rod, v_j - axial velocity of the plasma jet, Ox and Oz - coordinate axes.

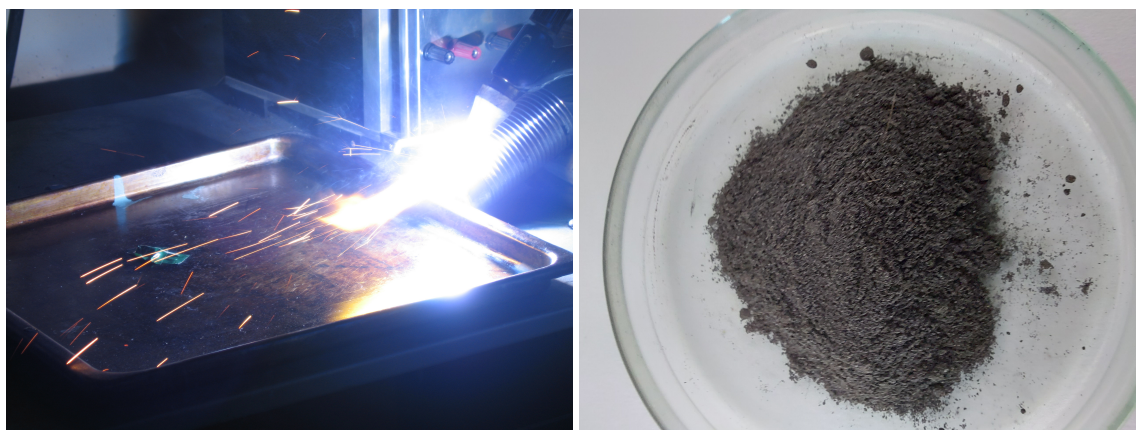


Figure A2. (Left panel). Visualization of argon plasma mixed with metal droplets (MD): the intensely bright region is the ArPJ, while the bright lines show an instance of the trajectory of MD. (Right panel) Resulted MMPs placed in a Petri dish.

Under these conditions, a steel rod with a diameter of 3 mm, introduced into the plasma at a speed $v_t = 1$ mm/s is instantly pulverized (Figure A2 - Left panel). The number of droplets per second, along the discharge axis Oz , is between 8×10^6 and 10^{13} . The MMPs (Figure A2 - Right panel) are obtained through vapor condensation and droplet formation at ambient temperature.

Appendix B. XRD and SEM Measurements

The crystalline structure and phase of MMPs with and without and lard, were studied using a PANalytical X'Pert Pro MPD diffractometer with Cu-K α radiation ($\lambda_{Cu} = 1.54060$ Å). Data were collected in the 2θ range from 20° to 80° with a collection time of 0.2 seconds per step.

The standard Rietveld technique using the FullProf program was applied for refinement and the structural parameters of the composites were calculated. The analysis of the diffraction spectra (Figure A3) shows that the position of the peaks of the diffractogram correspond to the phase identified according to the cubic space group Fd-3m of magnetite, according to the JCPDS card number: 01-088-0315. The major crystallographic peaks at diffraction angles $2\theta = 30.2^\circ, 35.5^\circ, 43.2^\circ, 53.6^\circ, 57.2^\circ, 62.9^\circ, 74.3^\circ$, corresponding to the (220), (311), (400), (422), (511), (440) and (533) reflections of magnetite.

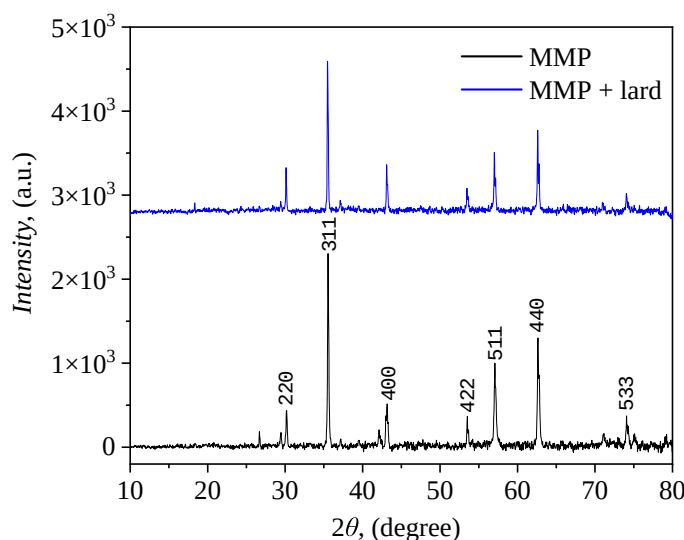


Figure A3. XRD data for MMPs, without and with lard.

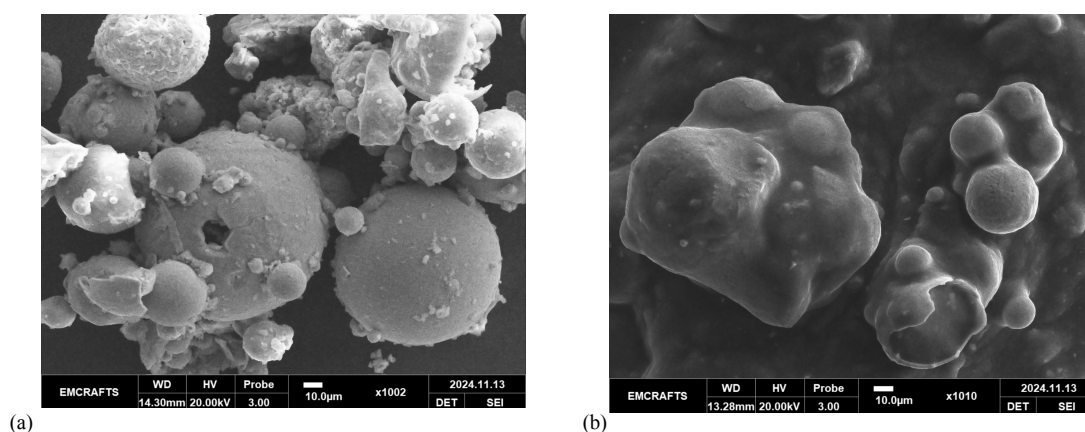


Figure A4. SEM images of MMPs, without lard (a), and with lard (b).

The surface morphological analysis of the MMPs without and with lard is studied by SEM (Figure A4). The composites were analyzed using the following working parameters: acceleration voltage of 30 kV, spot value of 3, magnification of 3000 x, in high vacuum mode. Thus, the qualitative analysis of materials based on Fe_3O_4 shows that the particles have a spherical shape, with dimensions of several tens of micrometers, which is in accordance with the results obtained by X-ray diffraction. In the case of the magnetite-lard compound, the SEM images have highlighted the fact that the magnetite particles are embedded in the lard.

Appendix C. Components of FC

We use the measurement cell shown in Figure A5 (Left panel). These are made up of two stratified textolite plates STP, as described in Section 2.5. On a STP plate, a silicone rubber ring (SRR) with a square cavity inside is fixed. In this cavity, MMPs and lard are alternately introduced, over which the second STP plate with the copper side is pressed. The resulting assembly is consolidated with an insulating adhesive tape produced by 3M (USA).

When MMPs are used, the resulting assembly is a flat capacitor. When lard is used, a second flat capacitor is obtained, denoted as FC_{lard} . A third capacitor $\text{FC}_{\text{cotton}}$ is obtained when, instead of the SRR with MMPs or lard, we use only a cotton fabric, as shown in Figure A5 (Right panel).

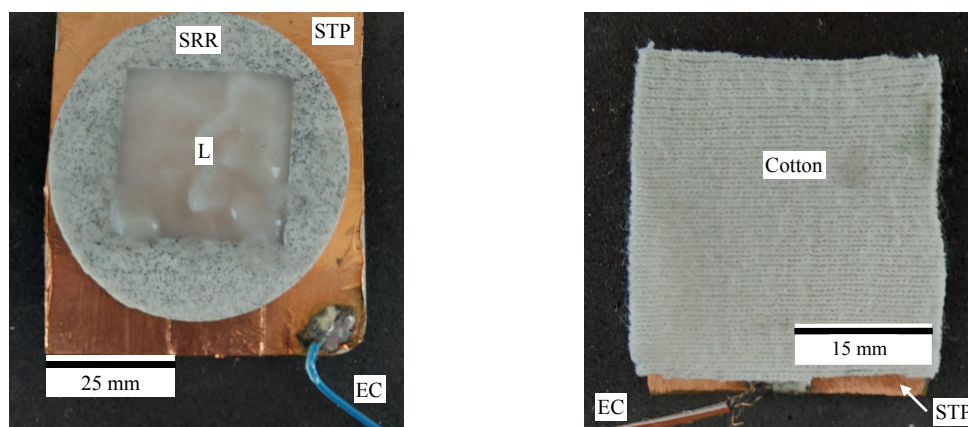


Figure A5. Measuring cell (without top stratitextolite STP) used for electrical measurements. (Left panel) With lard. When MMPs are used, they replace lard from within the SRR. (Right panel) With cotton fabric. SRR - silicone rubber ring, EC - electrical connector.

Appendix D. Measurement of Electrical Properties

For measurements of the electrical properties of MMPs and lard, we use the measurement cell shown in Figure A5 (Left part). Alternatively, for cotton fabric, the measurement cell from Figure A5 (Right part) is utilized. The experimental setup used is described in Section 2.6.

The capacitors are sequentially placed between the N and S poles of the electromagnet. By adjusting the intensity of the electric current supplied to the electromagnet coil, the magnetic field is set to achieve specific values $B = 0.300 \text{ mT} \pm 0.05 \text{ mT}$.

The assembly, consisting of the FC and Hall probe h, is secured by applying a non-magnetic mass to the platform mounted on axis 3, as shown in Figure 6, creating a compressive force $F = 1 \text{ N}$. Using the Br bridge, model CHY-41R (made in Taiwan), measurements are taken at a frequency of $f = 1 \text{ kHz}$ and at a specified voltage $U = 0.8 V_{\text{eff}}$ to determine C and the dielectric loss coefficient D . The measured values are presented in Table 1.

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