How can MAGNETISM contribute to environmental sustainability?

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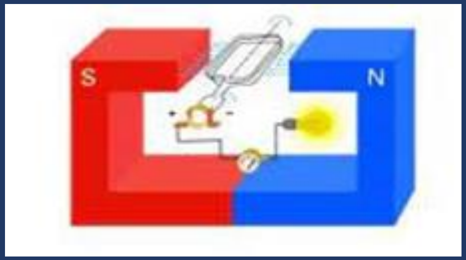
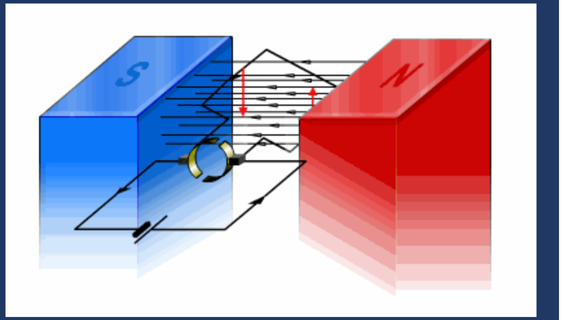
Santander, 08/11/2024

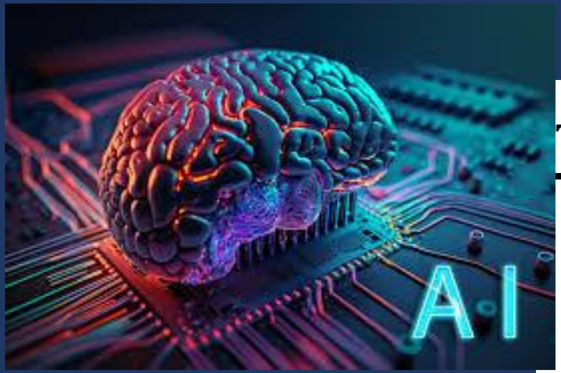
MAGNETISM
&
Environmental Sustainability

ELECTRIC GENERATOR



ELECTRIC MOTORS





Technology

EL PAÍS

JUL 16, 2024 ·

AI >

Artificial intelligence is already an environmental problem

The energy and water consumption of Google and Microsoft, the main developers of generative AI, as well as their carbon emissions, have skyrocketed for the second consecutive year

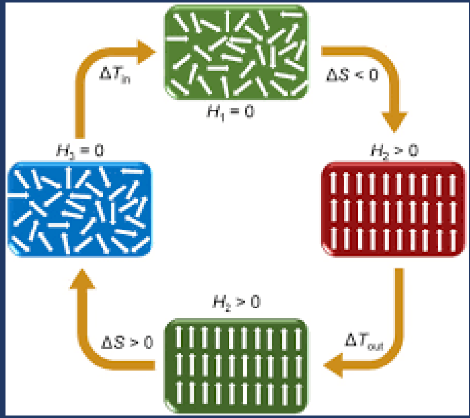
SPINTRONICS

SPINRED2

Red Española de Espintrónica

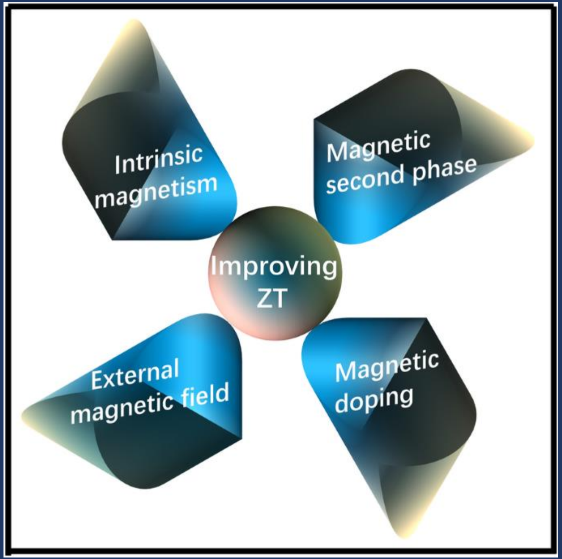
Explorando el uso de la espintronica para el desarrollo de dispositivos de bajo consumo de energia

MAGNETIC REFRIGERATION



MAGNETOCALORIC EFFECT

THERMOELECTRICITY



https://doi.org/10.1007/s12598-020-01652-6

upna
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Institute for Advanced Materials and Mathematics

Research group: Propiedades Físicas y Aplicaciones de Materiales
http://www.unavarra.es/propiedades-aplicaciones-materiales

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(1) VIBRATIONAL ENERGY HARVESTERS

(2) WATER REMEDIATION

A humble contribution…….

(1) VIBRATIONAL ENERGY HARVESTING

WIKIPEDIA The Free Encyclopedia

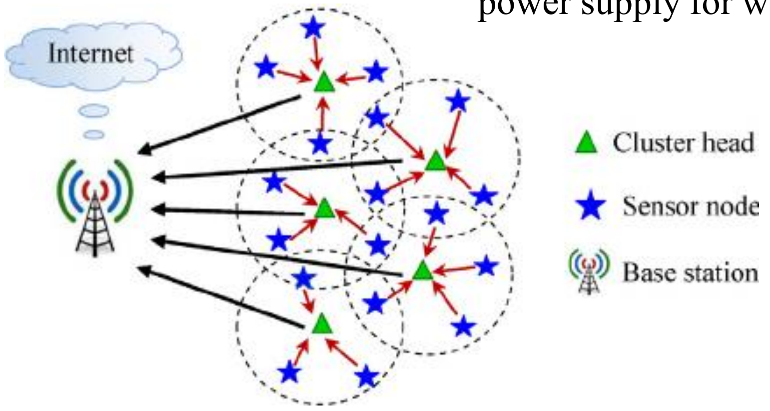
ENERGY HARVESTING

process by which energy is derived from external sources (e.g., solar power, thermal energy, wind energy and kinetic energy, also known as ambient energy), captured, and stored for small, wireless autonomous devices, like those used in **wearable electronics** and **wireless sensor networks**

conversion of **ambient energy** present in the environment into electrical energy

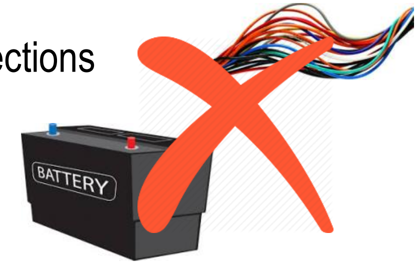
Wireless Sensor Networks (WSN)

power supply for wireless self-powered microsystems



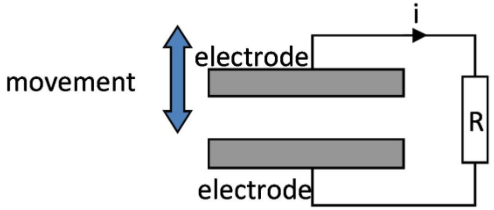
wired energy connections

battery power

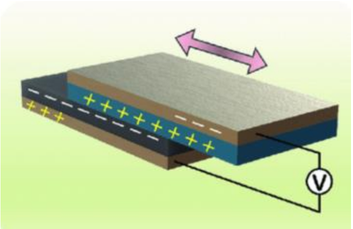


(1) VIBRATIONAL ENERGY HARVESTING

Electrostatic



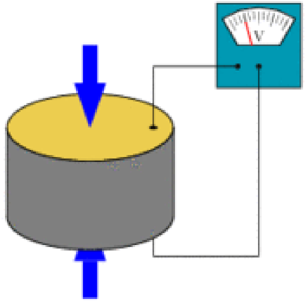
Triboelectric

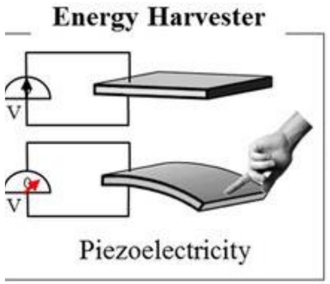


Piezoelectric

f_r = 49 Hz

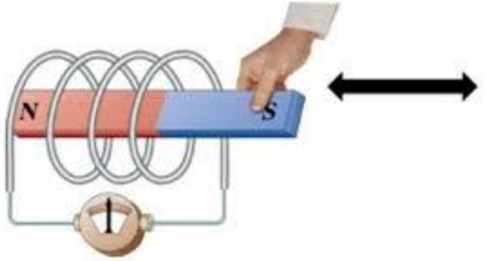
PIEZO.COM



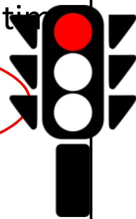


Electromagnetic

Faraday-Lenz law

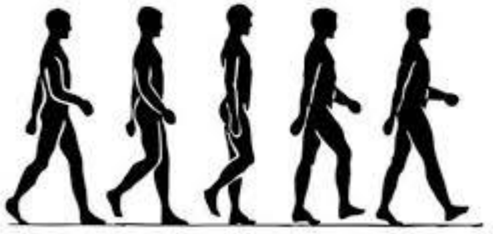


Transduction Mechanism	Power density	Advantages	Disadvantages
Piezoelectric	4-250 μW/cm^3	• High voltage and high energy density • No external voltage • Small mechanical damping • Simple design , resonant frequency easily tuned) • Easy voltage rectification	• Highly variable output • Low output current and power (high impedance) • Degradation of the piezoelectric material over time • **Self-discharge at low frequencies** • Difficult integration with microelectronics
Electromagnetic	300-800 μW/cm^3	• High output currents and power • Robustness (long-life) • Small mechanical damping • Low-cost design • MEMS compatibility with planar coil and springs	• Relatively large size (difficulties to miniaturize the size to microscale and to integrate with microelectronics) • Coil ohmic losses • Low output voltage, complicated rectification • Decrease of the efficiency at lower frequency



(1) VIBRATIONAL ENERGY HARVESTING

Source of vibration	Frequency (Hz)	Acceleration (m/s^2)
Door frame after door closes	125	3
Windows near busy road	100	0.7
Base of machine tool	70	10
Air conditioning vents in office building	60	0.2 - 1.5
Car instrument panel	13	3
HVAC ducts, fan belt cages	15.5 - 60.6	< 3
Bridge vibrations	< 15	< 0.5

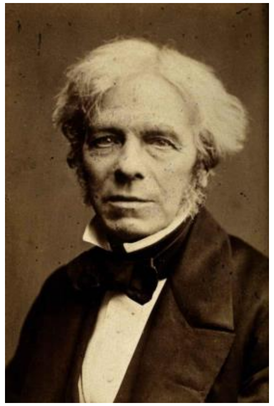


Frequency ≈ 2 Hz

Frequency ≈ 1 Hz

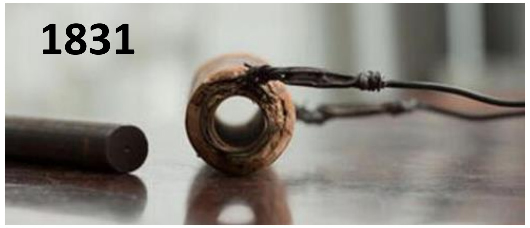
Frequency ≈ 6-30 Hz

(1) VIBRATIONAL ENERGY HARVESTING



DESIGN AND OPTIMIZATION OF SMALL ELECTROMAGNETIC HARVESTERS FOR VIBRATIONAL ENERGY SCAVENGING

TED2021-130884B-I00

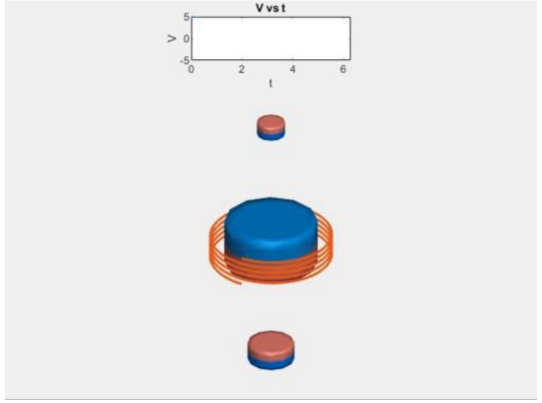


Funded by the European Union
NextGenerationEU

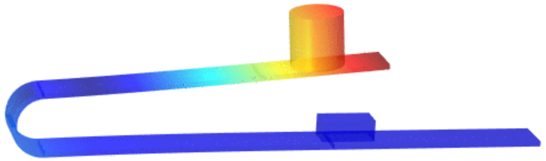
Plan de Recuperación, Transformación y Resiliencia

RESONANT SYSTEMS

Magnetic levitation harvesters ← **RESONANT SYSTEMS** → *Magnetostrictive harvesters*



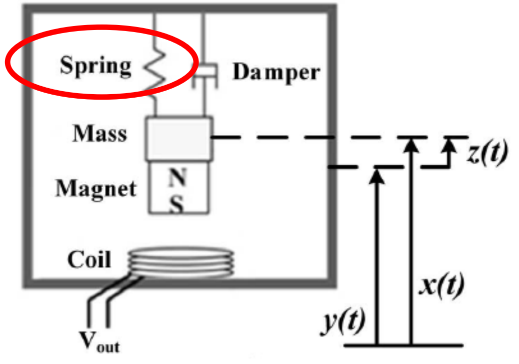
Matching with the *frequency* of the environmental vibration



(1) VIBRATIONAL ENERGY HARVESTING

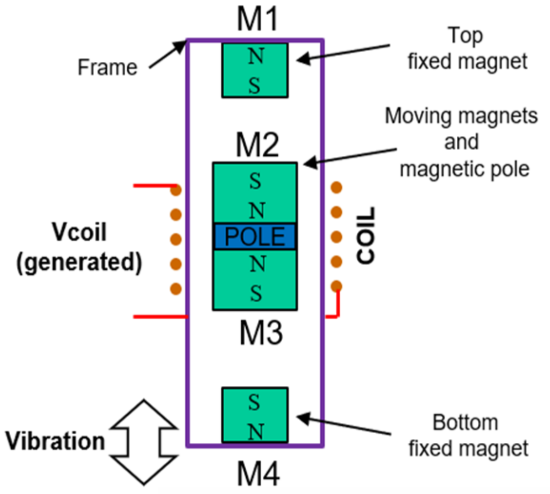
MAGNETIC LEVITATION HARVESTERS

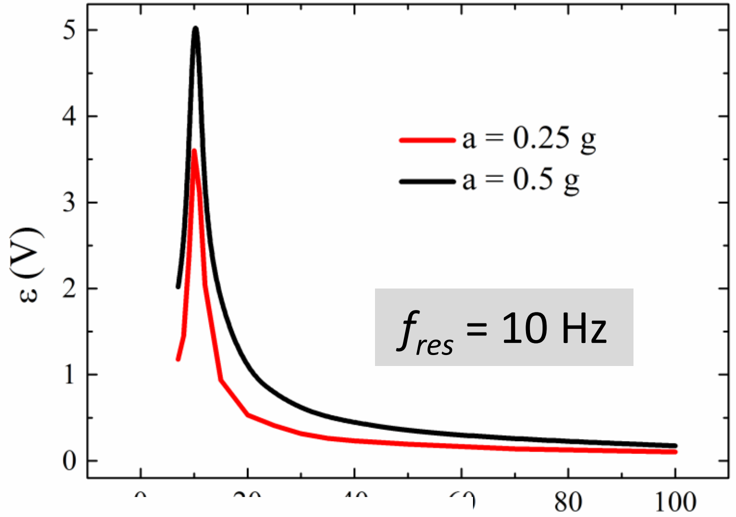
MAGNETIC SPRING

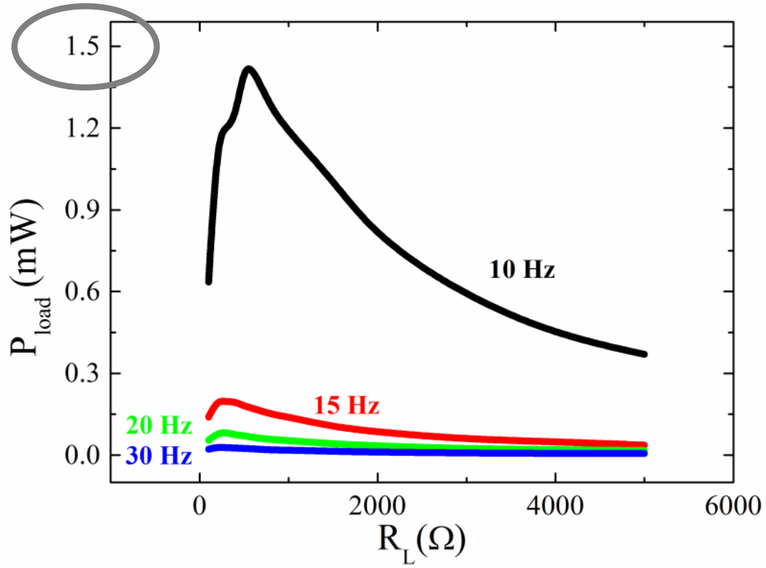


Q. Zhang, E. S. Kim, Proc. IEEE 102 (11) (2014) 1747-1761. doi: 10.1109/JPROC.2014.2358995.

J.J. Beato-Lopez, I. Royo-Silvestre, J.M. Algueta-Miguel, C. Gómez-Polo, Sensors 20(7) (2020) 1873.



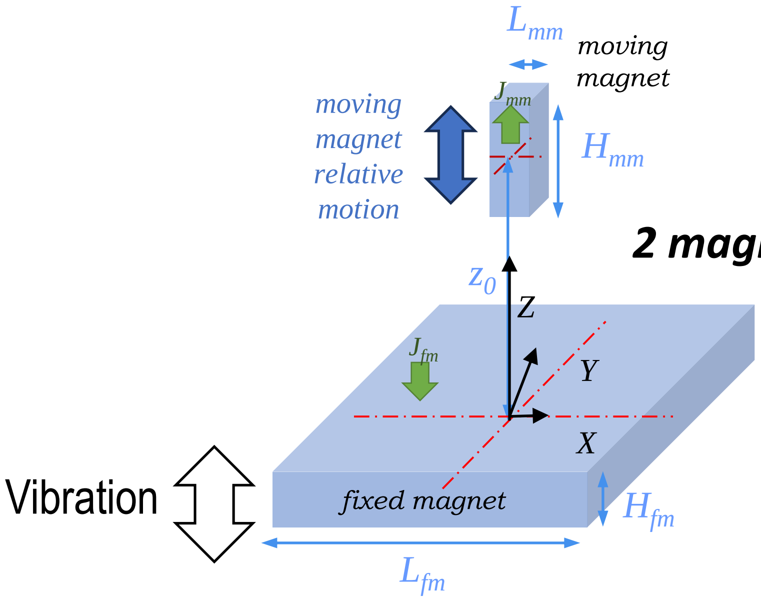




(1) VIBRATIONAL ENERGY HARVESTING

MAGNETIC LEVITATION HARVESTERS

I. Royo-Silvestre, J.J. Beato-López, C. Gómez-Polo, Appl. Energy 360 (2024) 122778.



2 magnets in repulsion → $\vec{F}_{mag}$

$$k_{mag}(z_0) = -\left.\frac{dF_{mag}}{dz}\right|_{z=z_0}$$

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{k_{mag}(z_0)}{m}}$$

ANALITICAL

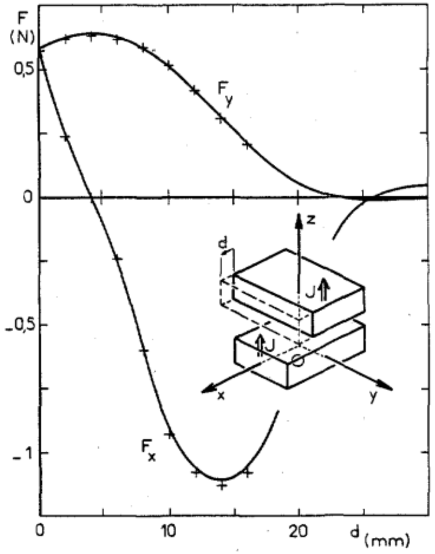


FIG.2 Experimental verification (analytically calculated curves and measured points).

G. Akoun and J.-P. Yonnet, "3D analytical calculation of the forces exerted between two cuboidal magnets," *IEEE Trans. Magn.*, vol. 20, no. 5, pp. 1962–1964, Sep. 1984, doi: 10.1109/TMAG.1984.1063554.

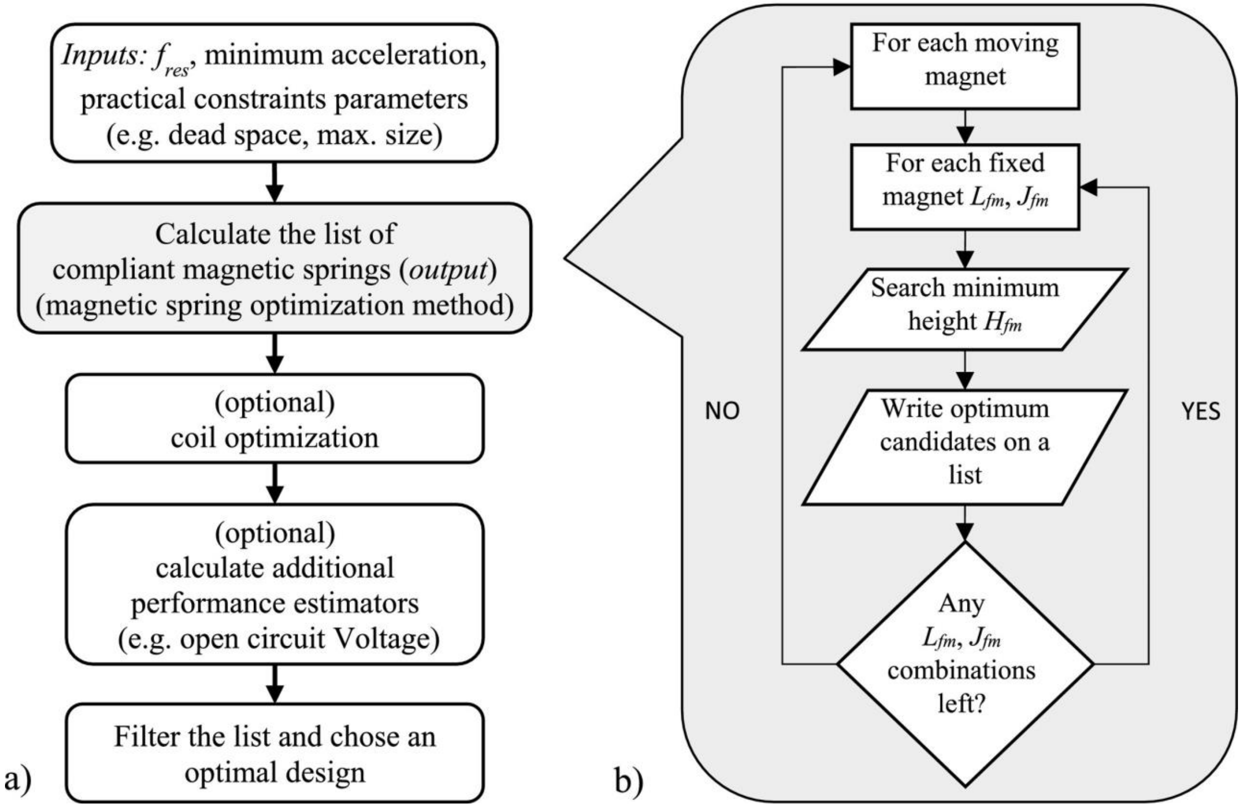
How many different magnet configurations provide the desired resonance frequency?

AUTOMATED SEMI-ANALYTICAL DESIGN →

MAGNETIC LEVITATION HARVESTERS

(1) VIBRATIONAL ENERGY HARVESTING

$$V(t) = k_e \frac{dz}{dt};\ \ k_e = -\frac{d\phi}{dz}$$



$L_{fm}xH_{fm}$ (mm)	$L_{mm}xH_{mm}$ (mm)	J_{fm} (T)	J_{mm} (T)	z_0 (mm)	f_{res} (Hz)	V_{pi} (V)
190x10	4x8	0.4	0.4	61	1.06	1.8
240x5	4x8	1.3	0.4	82	1.1	1.8
230x7	4x8	0.4	1.3	77	1.09	5.8
250x2.5	4x8	1.3	1.3	80	0.92	6.8
170x8	4x16	0.4	0.4	54	1.04	1.9
240x5	4x16	1.3	0.4	81	1.08	1.8
230x7	4x16	0.4	1.3	77	1.07	6.0
250x2.5	4x16	1.3	1.3	80	0.89	7.2
190x10	6x8	0.4	0.4	61	1.06	2.6
240x5	6x8	1.3	0.4	82	1.10	2.5
230x7	6x8	0.4	1.3	78	1.09	8.3
250x2.5	6x8	1.3	1.3	80	0.92	9.8

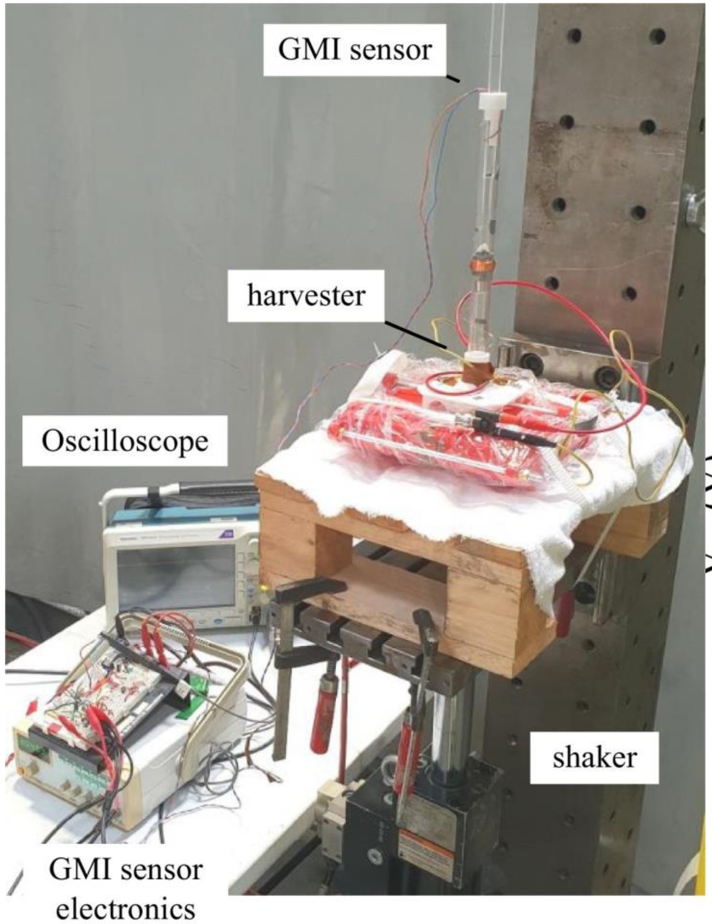
$L_{fm}xH_{fm}$ (mm)	$D_{mm}xH_{mm}$ (mm)	***Fixed magnet***	***Moving magnet***	z_0 (mm)	f_{res} (Hz)
200x20	15x30	Ferrite Y35	NdFeB N42	158	1.9

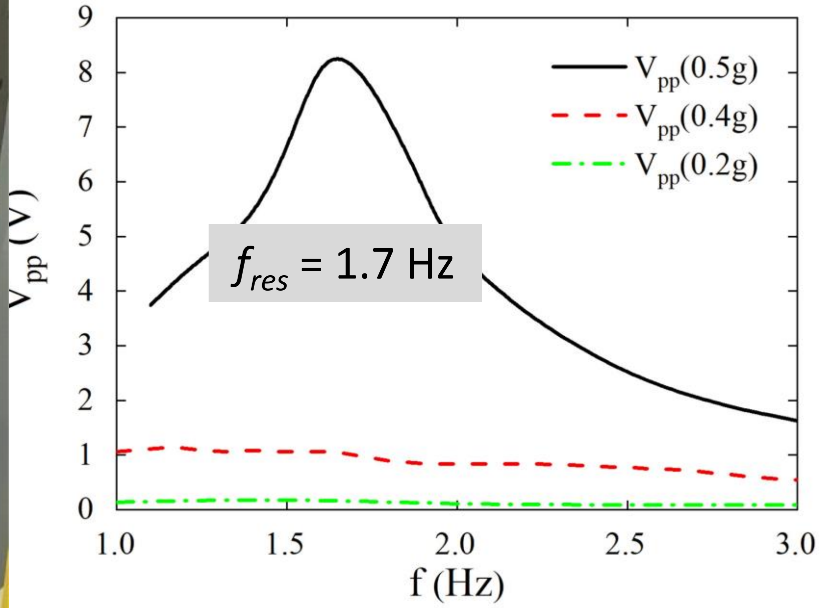
The design for the final protype, checked by 3D FEA. Rectangular fixed magnet, cylindrical moving magnet (D_{mm}: moving magnet diameter)

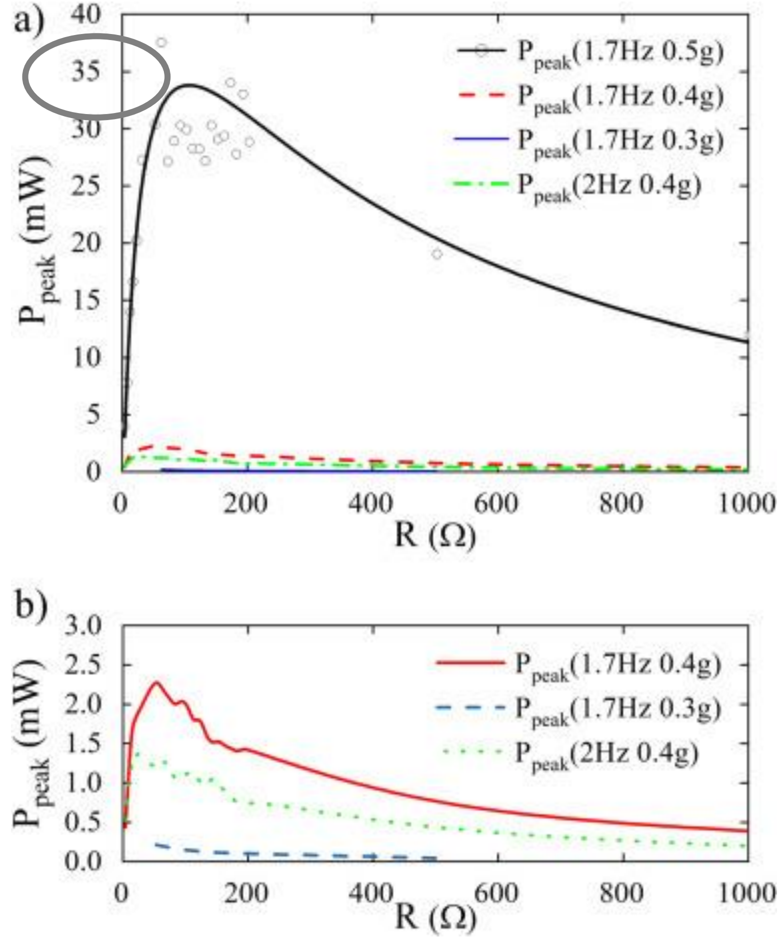
(1) VIBRATIONAL ENERGY HARVESTING

MAGNETIC LEVITATION HARVESTERS

Experimental Characterization

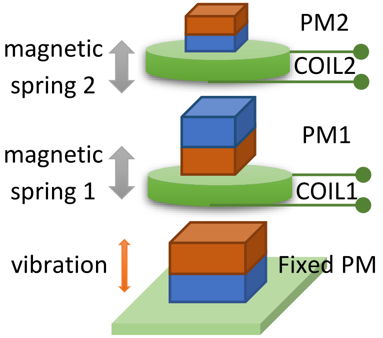






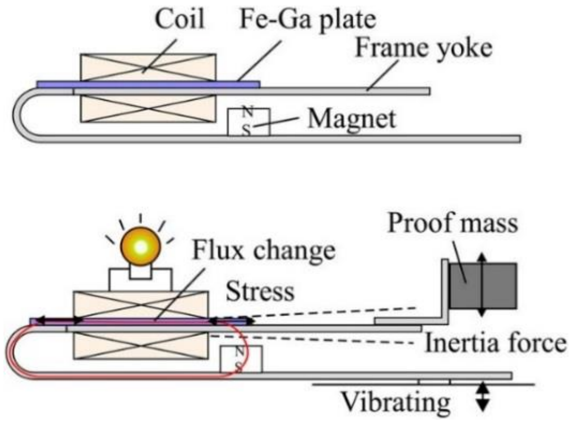
✓ Reduction of the harvester size

✓ 2DoF magnetic levitation based harvester



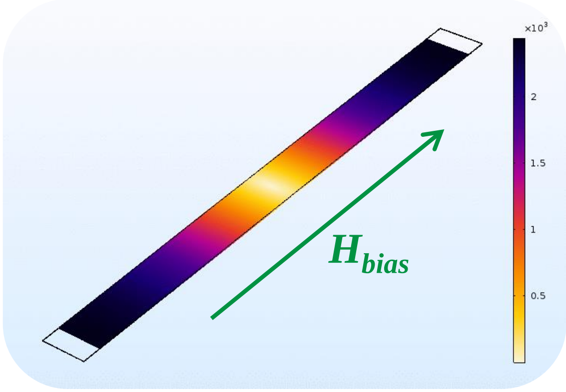
(1) VIBRATIONAL ENERGY HARVESTING

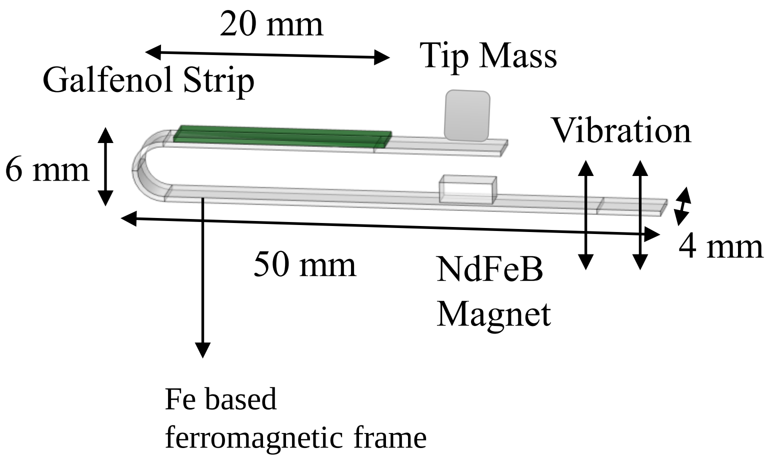
MAGNETOSTRICTIVE HARVESTERS



T. Ueno, AIP Adv. 9 (2019) 035018.

Magnetostriction-Magnetoelasticity





Optimum activation of Fe-Ga strip?

EXPERIMENTAL CHARACTERIZATION

FINITE ELEMENT METHOD (FEM) SIMULATIONS

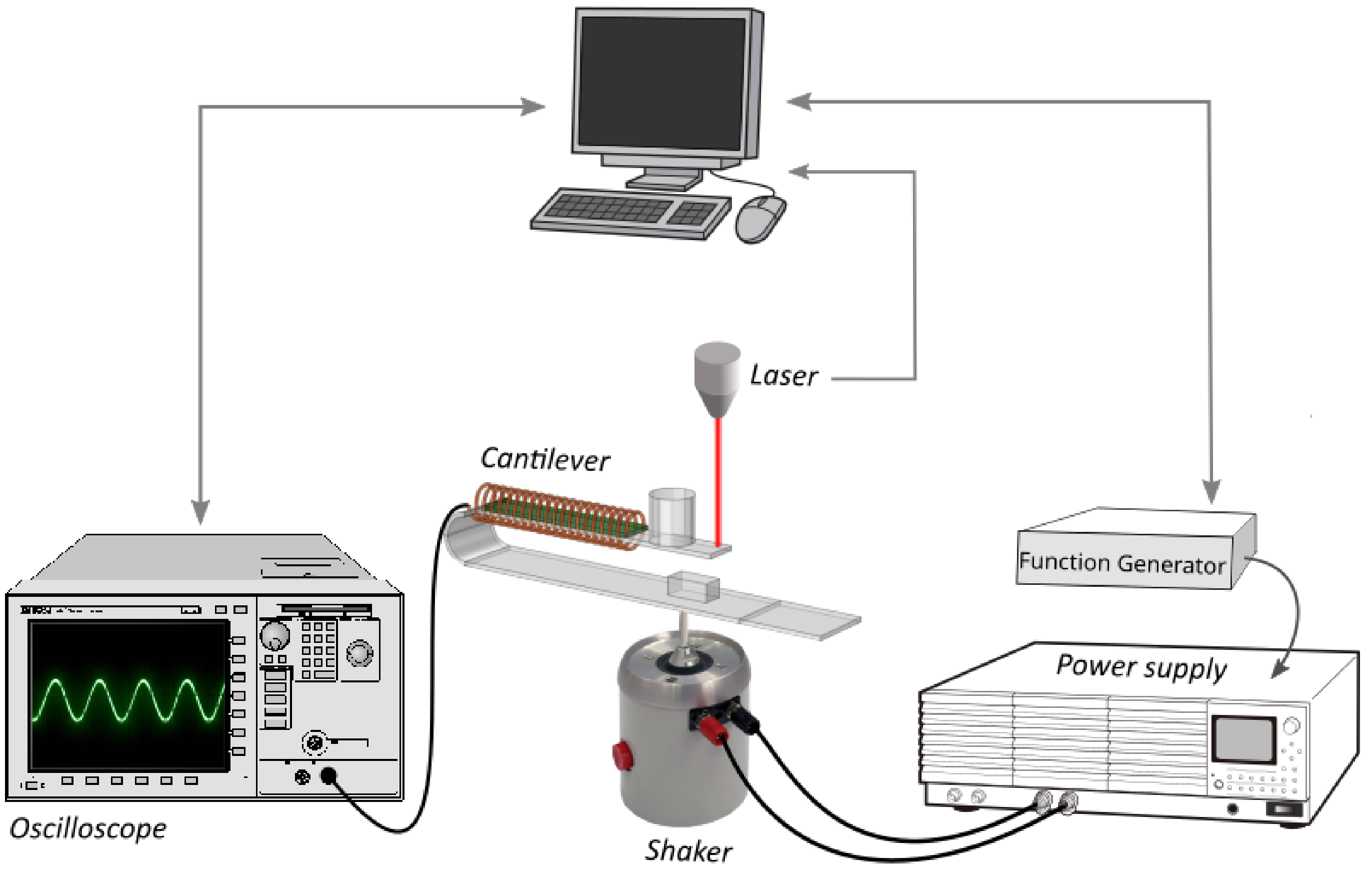
MATLAB+FEMTools
Open source software

Mechanical simulation — *Energy lost due to damping*

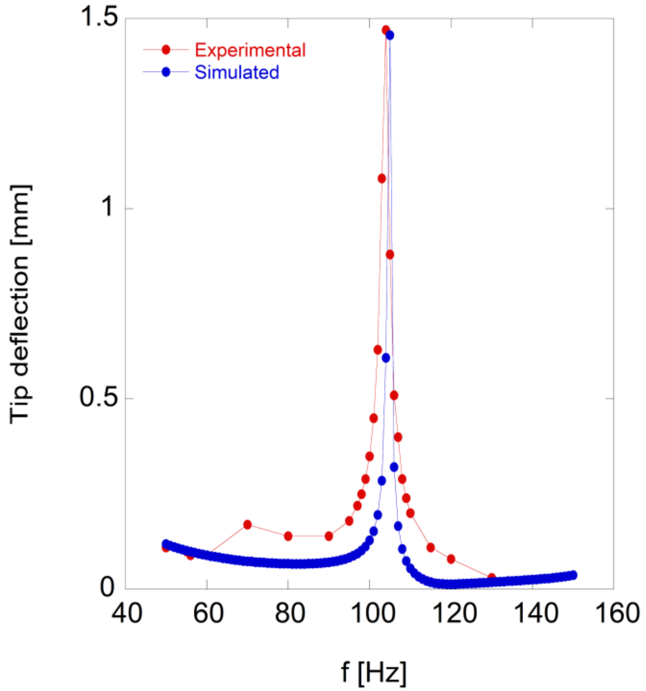
Electromagnetic simulation — *B distribution*

(1) VIBRATIONAL ENERGY HARVESTING

MAGNETOSTRICTIVE HARVESTERS



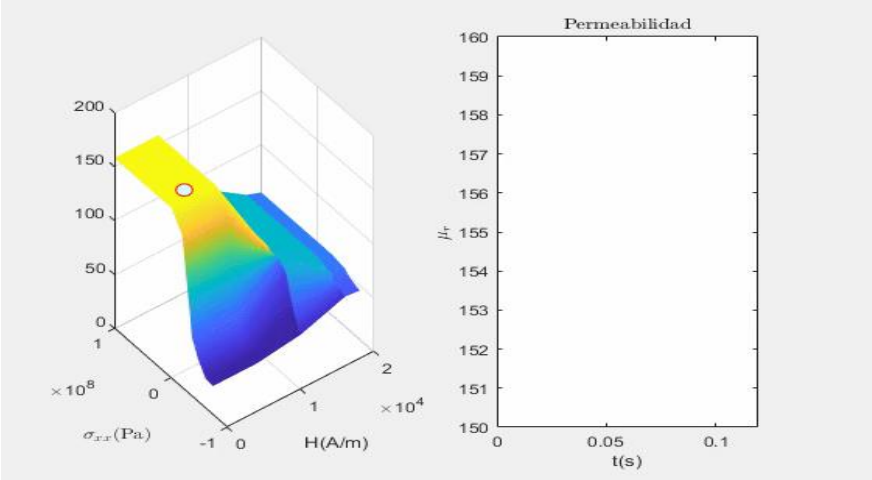
Tip Displacement

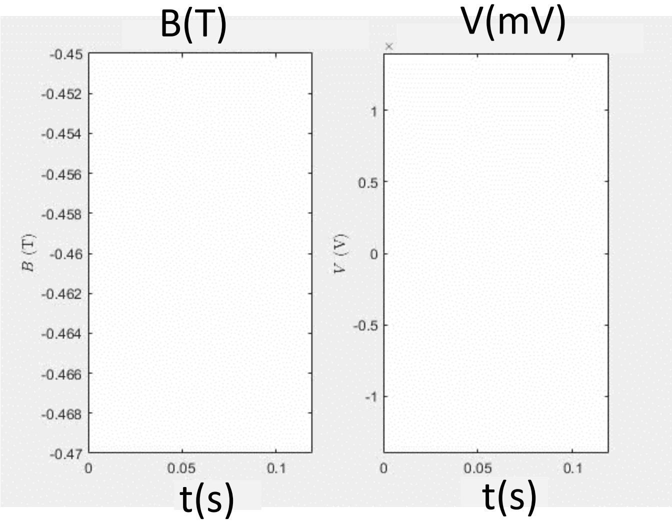


$$\frac{d^2u}{dt^2} + (\alpha + \beta w_o{}^2)\frac{du}{dt} + w_o{}^2 u = \frac{f(t)}{m}$$

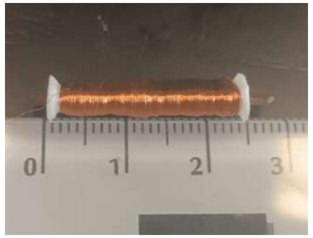
α: Stiffness-Proportional Damping
β: Mass-Proportional Damping

(1) VIBRATIONAL ENERGY HARVESTING



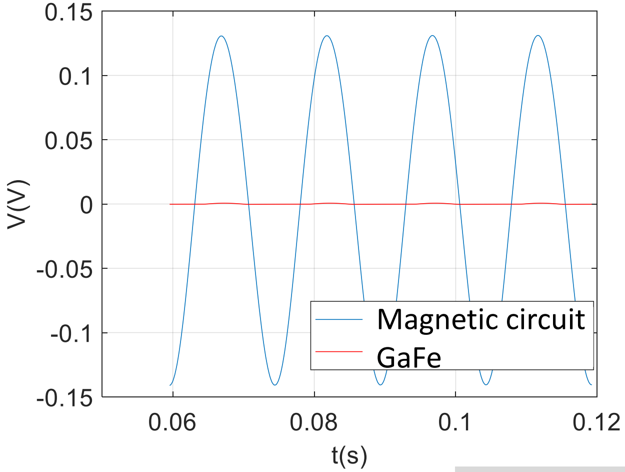


Optimized Parameters:
Coil Size: 3500 turns
Wire Size: 0.05 mm
Length of the pickup coil:
23 mm

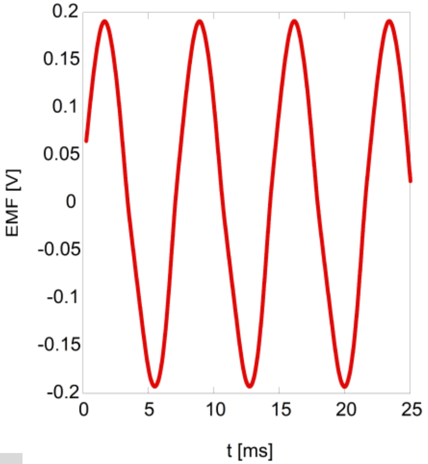


NEGLIGIBLE GaFe CONTRIBUTION!!!

FEM Results



Experimental Results



$a \sim 1$ g

f_{res} = 100 Hz

Higher amplitudes of the stress tensor(S)

Permanent magnets

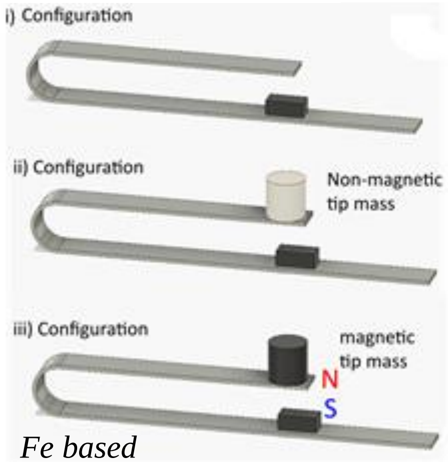
***L* = 10 cm**

(1) VIBRATIONAL ENERGY HARVESTING

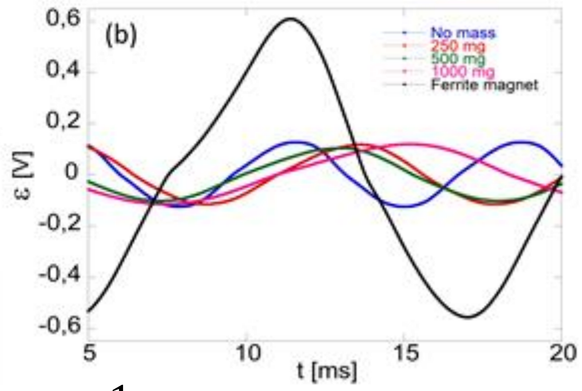
Optimum energy harvesting without GaFe strip?

D. Gandia, E. Garaio, J.J. Beato-López, I. Royo-Silvestre, C. A. de la Cruz Blas, S. Tainta, C. Gómez-Polo, Energy Convers. Manag.: X, 24 (2024) 100705.

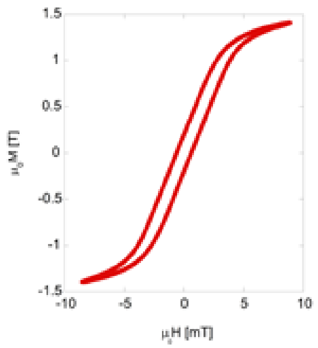
Tip mass **Ferrite Magnet** → f_{res} = 77 Hz



Fe based ferromagnetic frame



$a \sim 1$ g

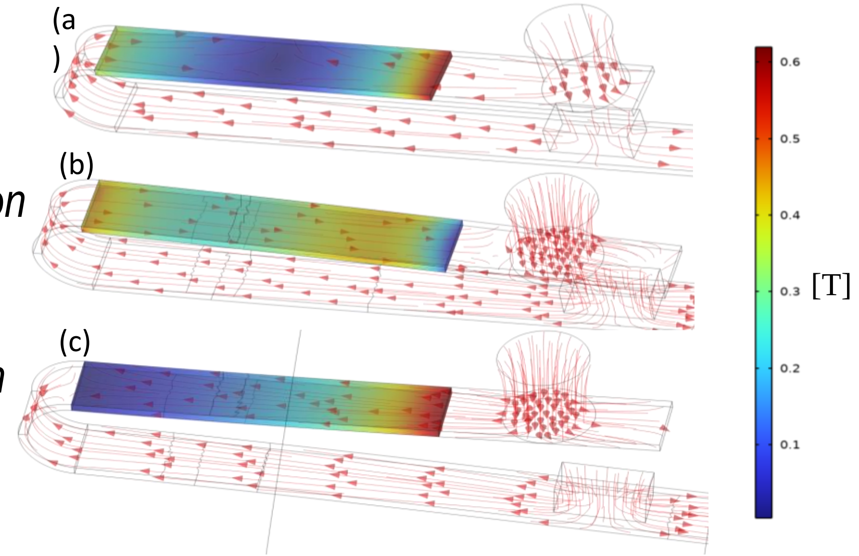


Changes on the magnetic flux (effective B) under vibration

Rest position

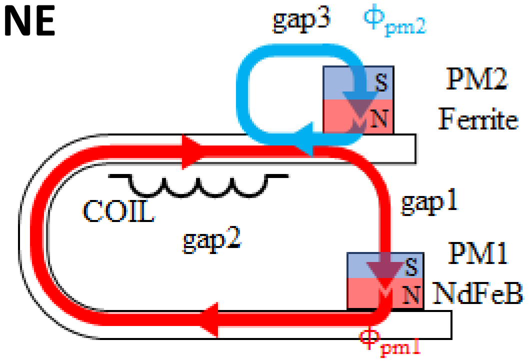
Minimum separation

Maximum separation



OCCURRENCE OF A NEUTRAL LINE

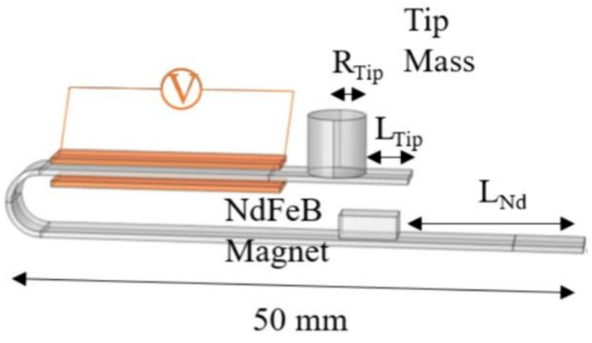
($B \approx 0$)



(1) VIBRATIONAL ENERGY HARVESTING

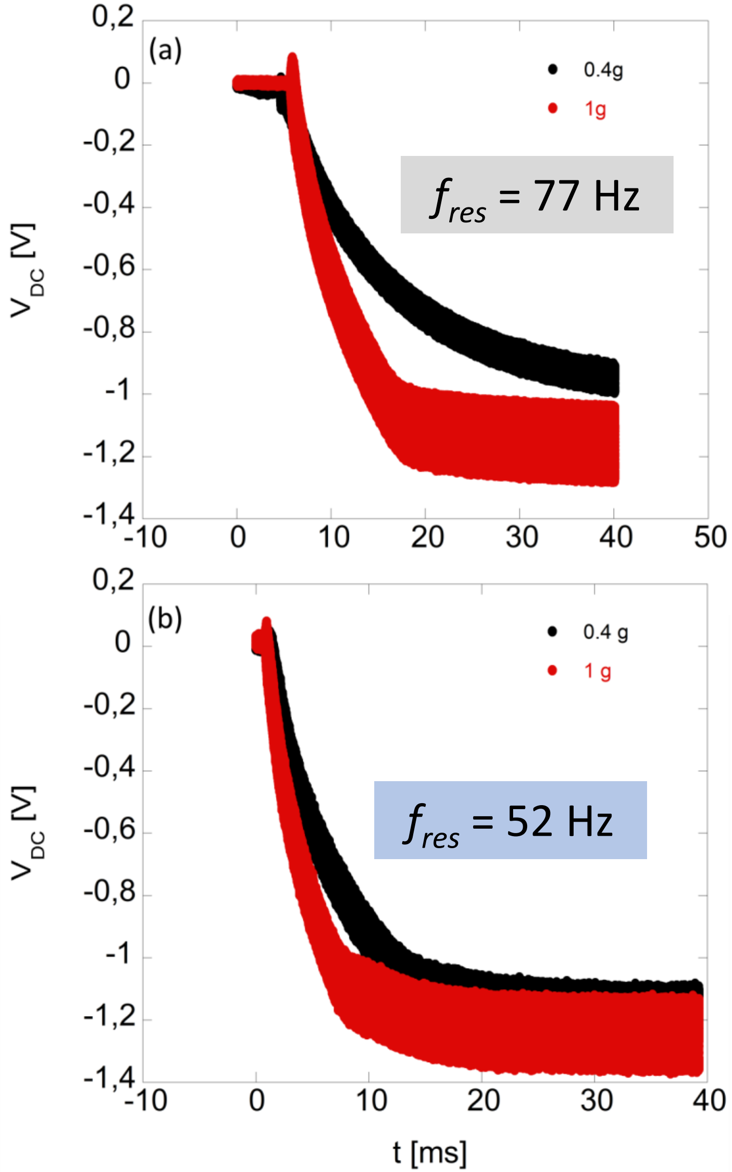
FEM Results

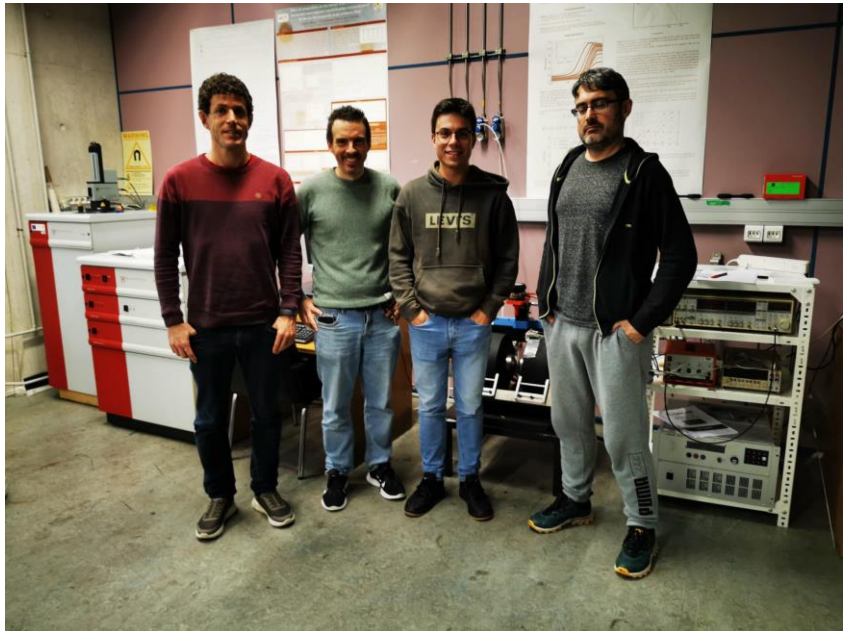
R_{tip} (mm)	*Mass* (mg)	f_r (Hz)
1.5	170	111
2.5	480	77
3.0	690	68
4.0	1220	63
5.0	1920	51



Experimental Results

DC Rectified voltage





INTERMAG 2025
January 13-17, 2025 • New Orleans, Louisiana

Symposium: Advanced Materials and Devices for Energy Harvesting and Conversion

Design and optimization of small electromagnetic harvesters for vibrational energy scavenging

(2) WATER REMEDIATION

Ensure availability and sustainable management of water and sanitation for all

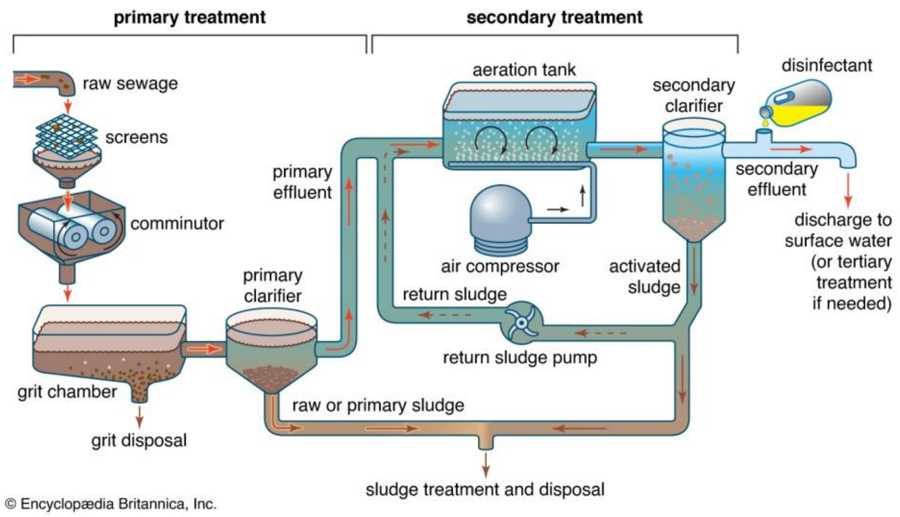
- 42% of household wastewater is not treated properly, damaging ecosystems and human health. (UN-Water, 2023)
- Only 11% of the estimated total of domest and industrial wastewater produced is currently being reused. (UNEP, 2023)
- Several water-related diseases, including cholera and schistosomiasis, remain widespread across many developing countries, where only a very small fraction (in some cases less than 5%) of domestic and urban wastewater is treated prior to its release into the environment. (UN WWDR, 2017)

WATER WASTE TREATMENTS

(2) WATER REMEDIATION

PRIMARY

wastewater is temporarily held in a settling tank where heavier solids sink to the bottom while lighter solids float to the surface.



SECONDARY

Degradation of the biological content of the waste through aerobic biological processes (bacteria).

Removal of 85% of the organic matter

TERTIARY

Removal of pathogens & Contaminants of Emerging Concern (**CECs**)
bacteria, viruses, and parasites

Pollutants that have been detected in water bodies, that may cause ecological or human health impacts, and typically are not regulated under current environmental laws

Biocides, disinfection-by-products, Industrial chemicals, personal care products, **pharmaceuticals (antibiotics)**

Antimicrobial resistance (AMR)

ADVANCED OXIDATION PROCESSES (AOPs) →

WATER WASTE TREATMENTS

ADVANCED OXIDATION PROCESSES (AOPs)

(2) WATER REMEDIATION

SEMICONDUCTOR PHOTOCATALYSIS

TiO_2, ZnO

UV absorption

Visible light absorption

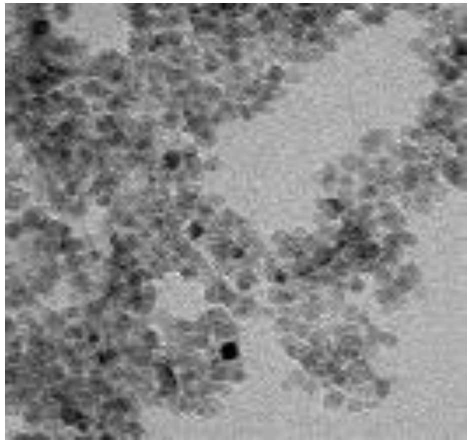
$$TiO_2 + h\nu \leftrightarrow h^+ + e^-$$
$$h^+ + H_2O_{absorbed} \leftrightarrow H^+ + {}^{\bullet}OH$$
$$h^+ + OH^-_{absorbed} \leftrightarrow {}^{\bullet}OH$$
$$e^- + O_{2\ absorbed} \leftrightarrow {}^{\bullet}O_2^-$$

Free radicals ⟶ **decomposition** organic substances

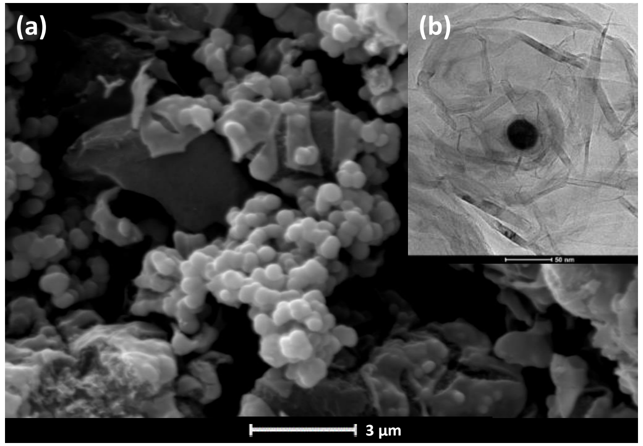
Effective **Magnetic Filtration**

REUSE AND RECYCLING

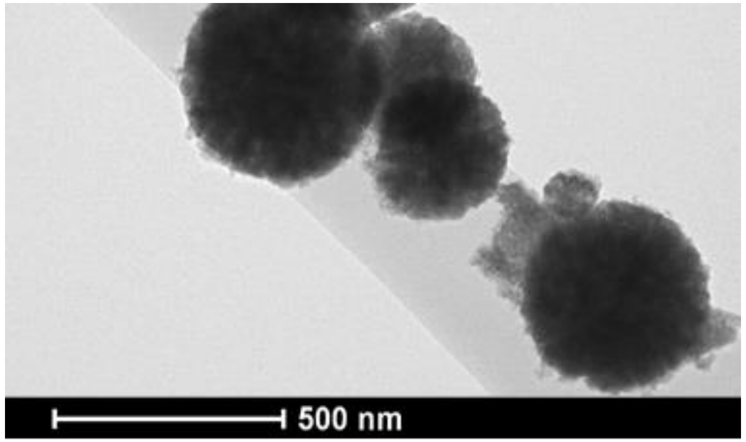
N-TiO_2 nanoparticles



Fe@C@TiO_2 nanostructures



Fe3O4@TiO_2 nanoparticles

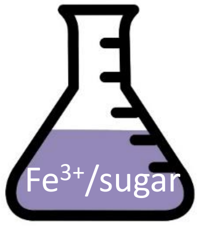


(2) WATER REMEDIATION

Fe@C@TiO_2 NANOSTRUCTURES

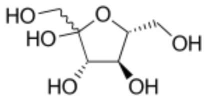
L. Cervera et al., J. Alloys Compd., 863 (2021) 158065

SYNTHESIS 1) Fe@C

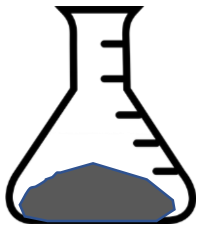


aqueous solution of $FeCl_3\ 6H_2O$
(10-30 wt.%Fe)

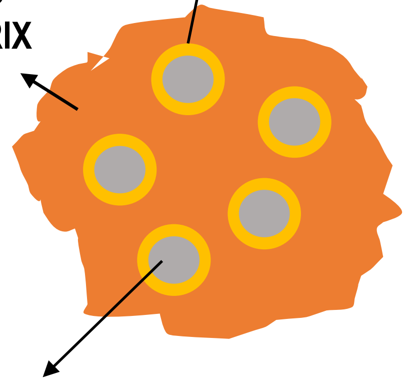
\+ Fructose



Evaporation
HEATING & STIRRING

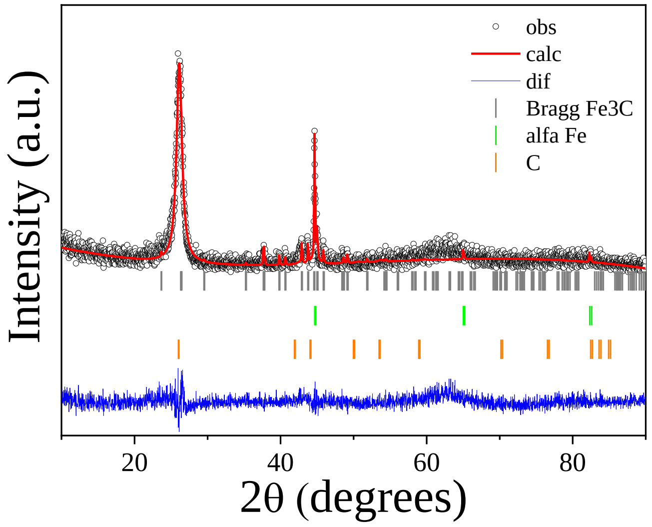


ANNEALING
Ar (1h)
800°C

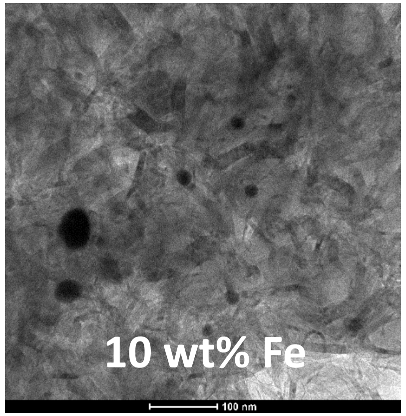


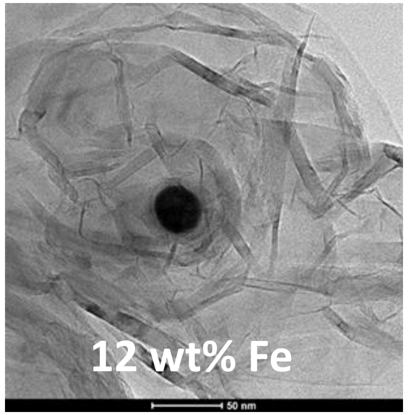
X-Ray Diffraction
Bruker D8 advance

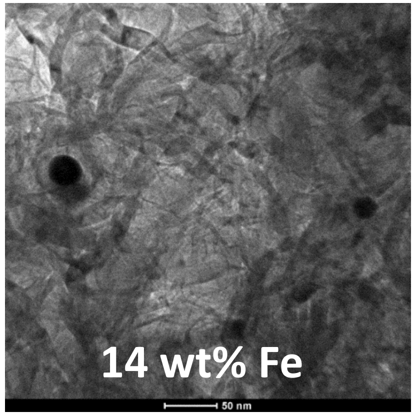
10 wt% Fe

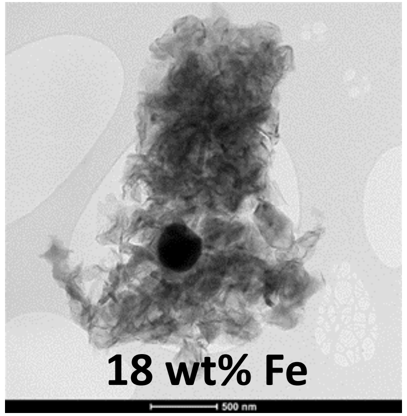


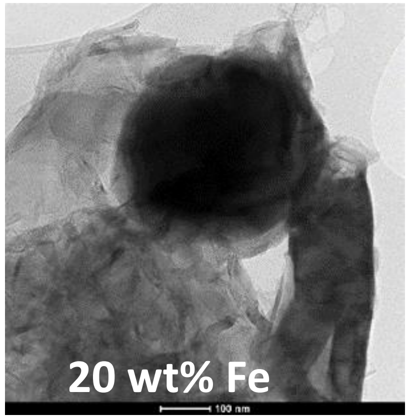
STRUCTURAL CHARACTERIZATION **TEM** Tecnai T20

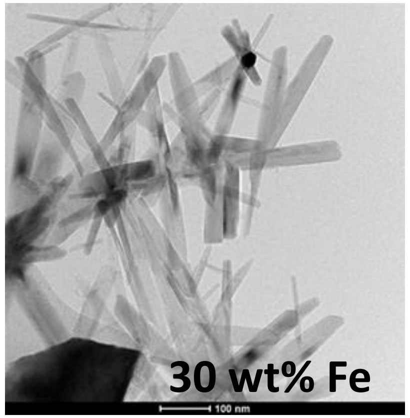












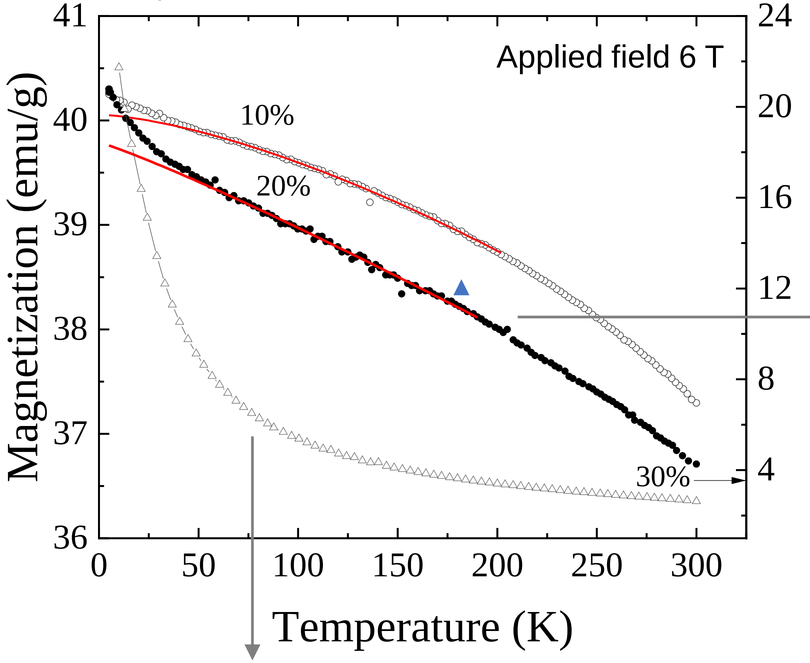
(2) WATER REMEDIATION

Fe@C@TiO_2 NANOSTRUCTURES

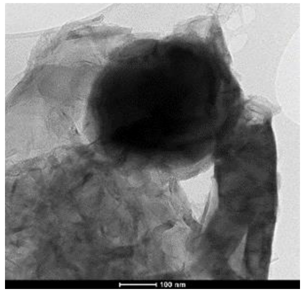
MAGNETIC CHARACTERIZATION

1) Fe@C

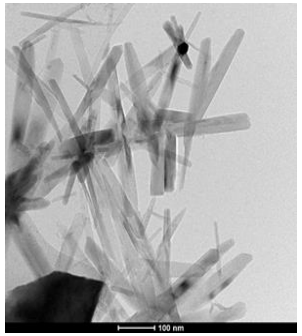
SQUID
Quantum Design XL-7

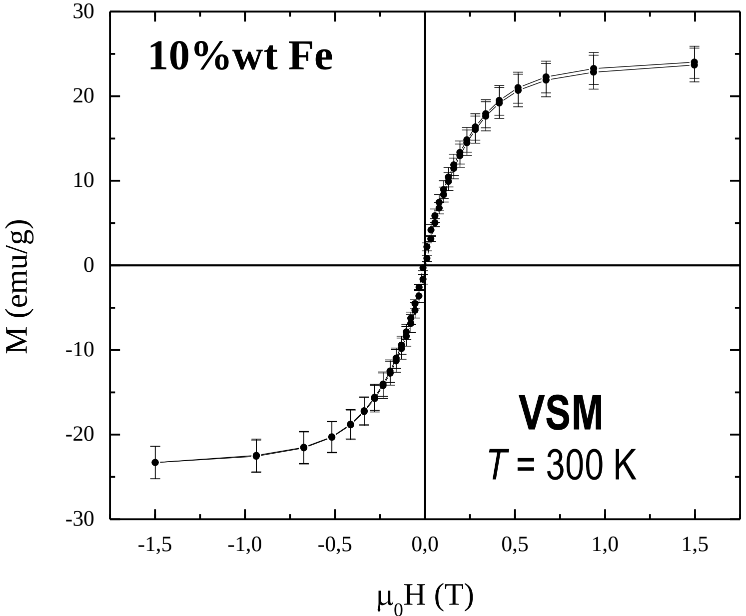


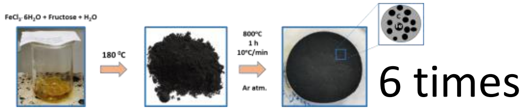
Oxidation



Oxidation





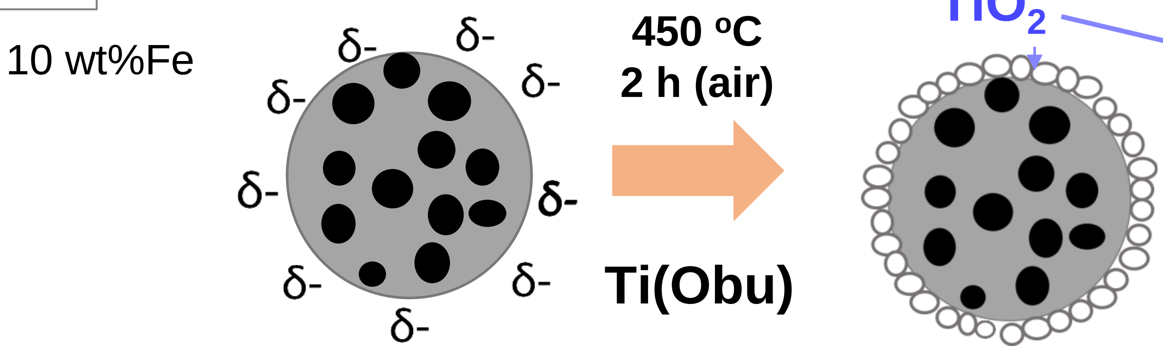


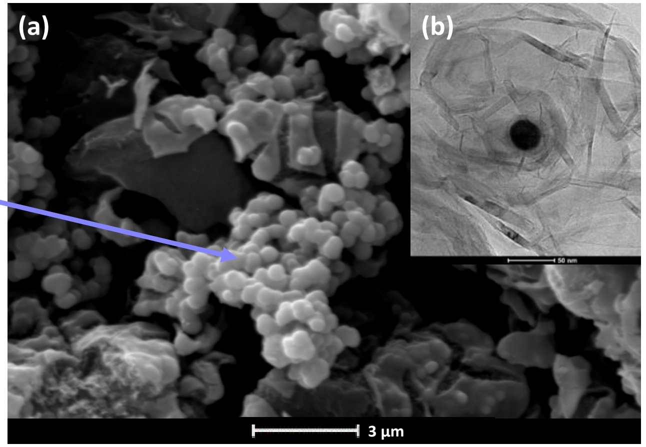
2) Fe@C@TiO_2

(2) WATER REMEDIATION

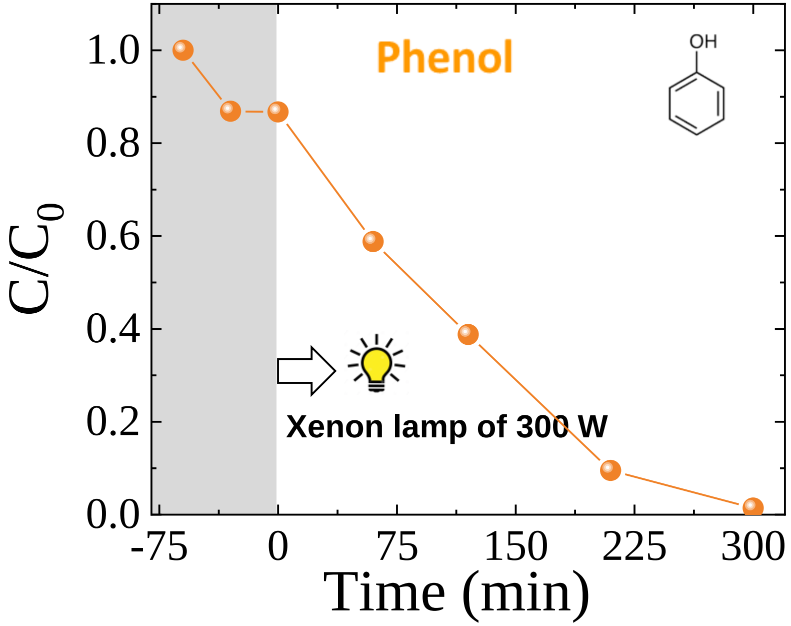
$Fe@C@TiO_2$ NANOSTRUCTURES

SYNTHESIS 2) $Fe@C@TiO_2$





PHOTOCATALYTIC CHARACTERIZATION



REUSE AND RECYCLING

✓ *Antibiotics degradation*

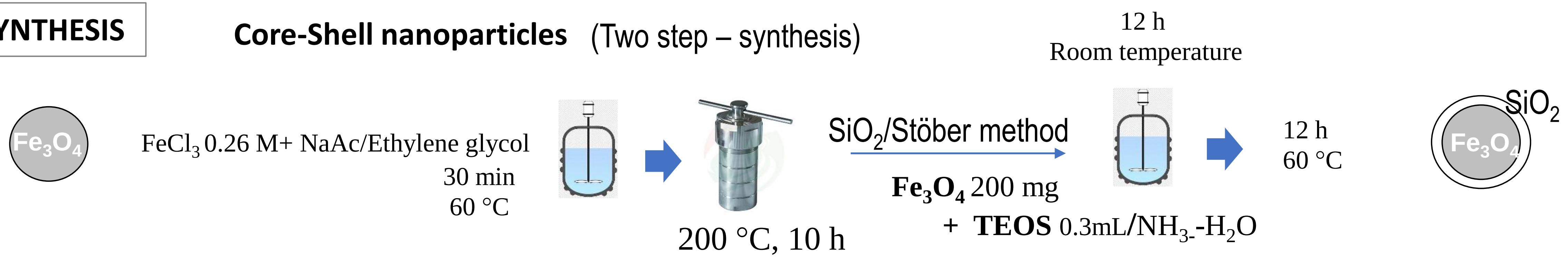
✓ *Use of carbon waste*

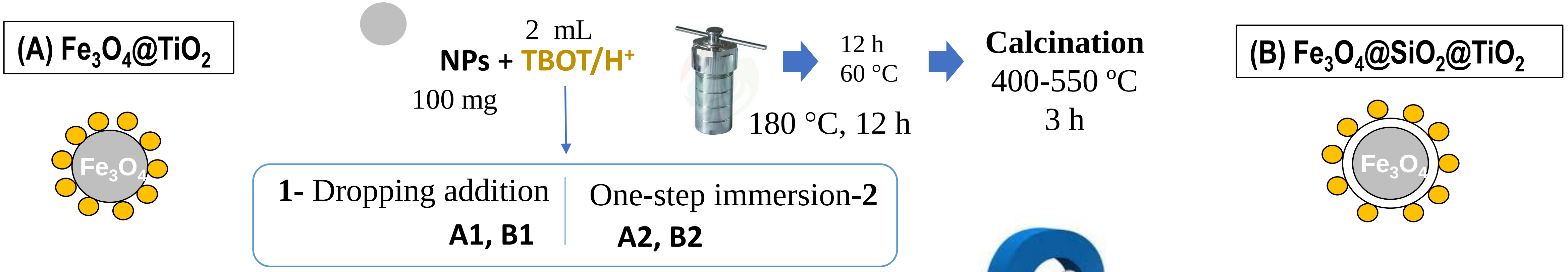
$Fe_3O_4@TiO_2$ NANOPARTICLES

(2) WATER REMEDIATION

SYNTHESIS

Core-Shell nanoparticles (Two step – synthesis)





Effect of SiO_2 coating?

Fe_3O_4@TiO_2 NANOPARTICLES

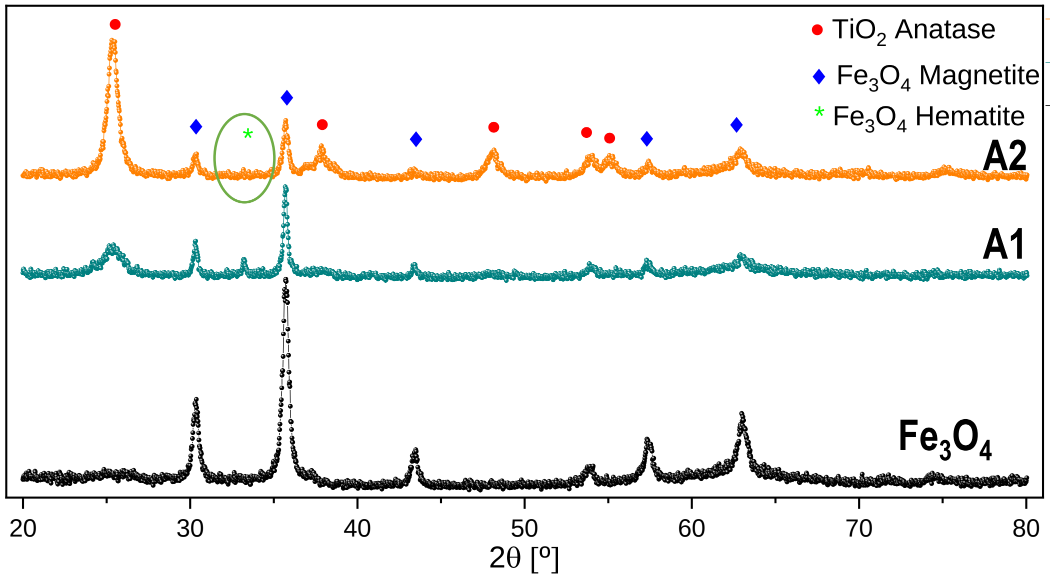
STRUCTURAL CHARACTERIZATION

(2) WATER REMEDIATION

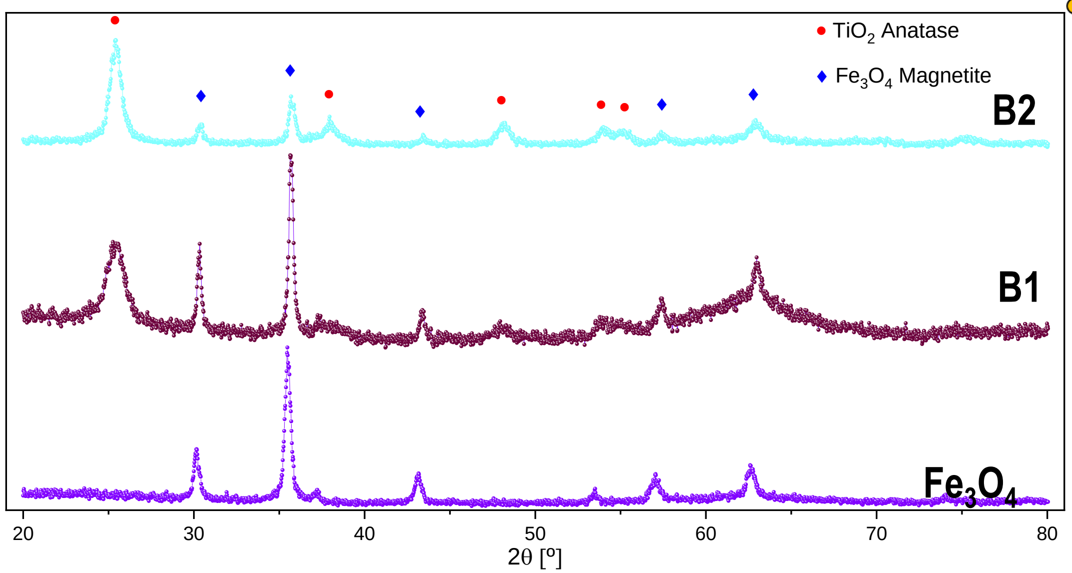
X-Ray Diffraction
Bruker D8 advance

T_{ann} = 450 °C

(A) Fe_3O_4@TiO_2



(B) Fe_3O_4@SiO_2@TiO_2



***Protective effect** of SiO_2 against Fe oxidation*

T_{ann} (°C)	Crystallite size TiO_2 (nm)				Crystallite size Fe_3O_4 (nm)			
	Sample				Sample			
	A1	**B1**	**A2**	**B2**	**A1**	**B1**	**A2**	**B2**
w. c.			3.4	7.8			19.9	17.9
400			2.9	6.9			17.8	17.9
450	6.1	7.4	10.7	10.3	28.6	24.7	28.9	20.2
500	7.4	7.6	12.6	10.3	25.1	24.1	24.8	20.3
550	9.7	10.5				24.6		

Optimum T_{ann} reduced Fe oxidation in ***A*** samples

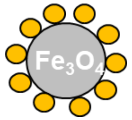
SiO_2 coating promotes slightly smaller Fe_3O_4 crystallite sizes

Fe_3O_4@TiO_2 NANOPARTICLES

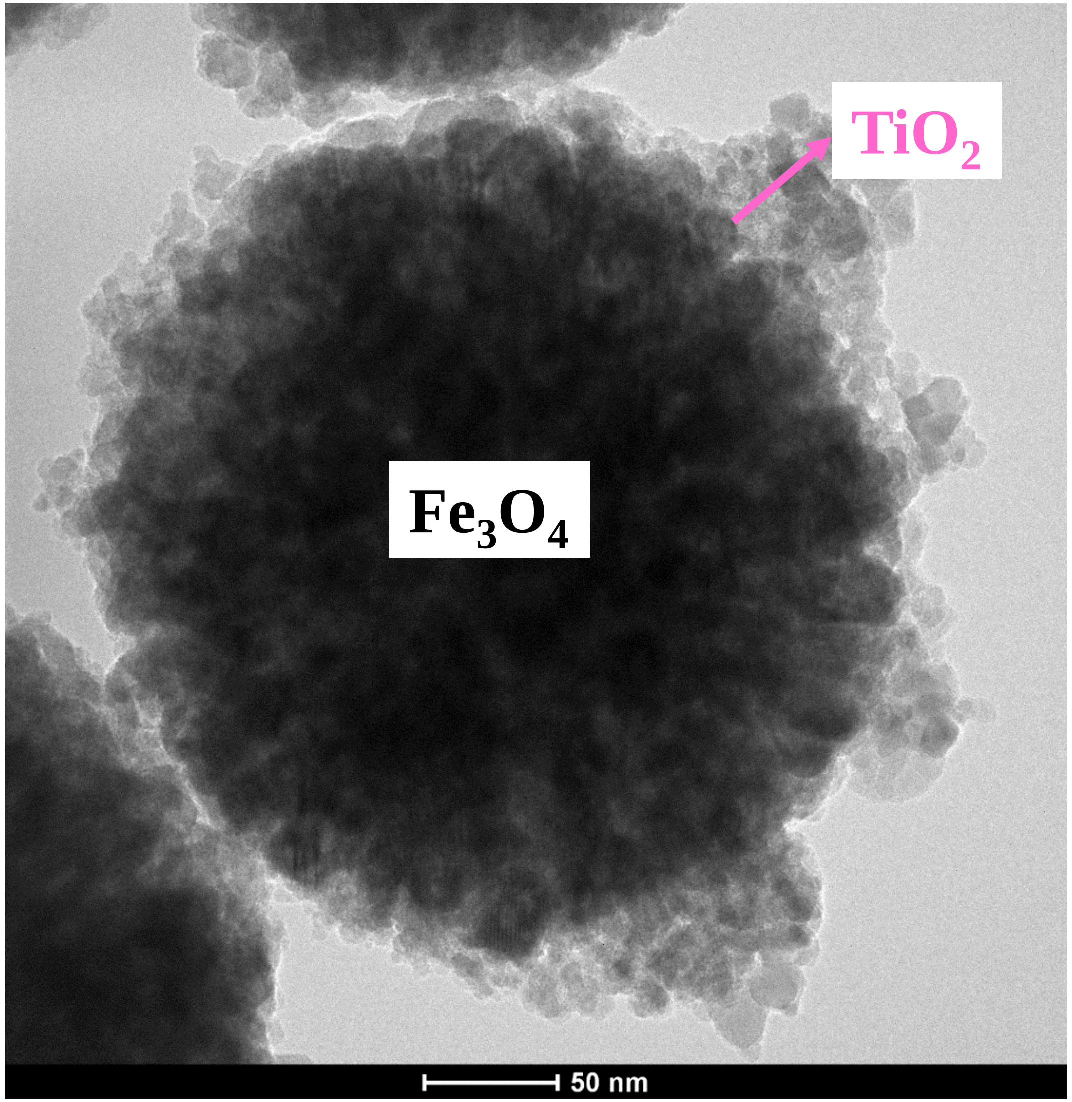
(2) WATER REMEDIATION

TEM
Tecnai T20

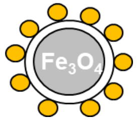
T_{ann} = 450 °C

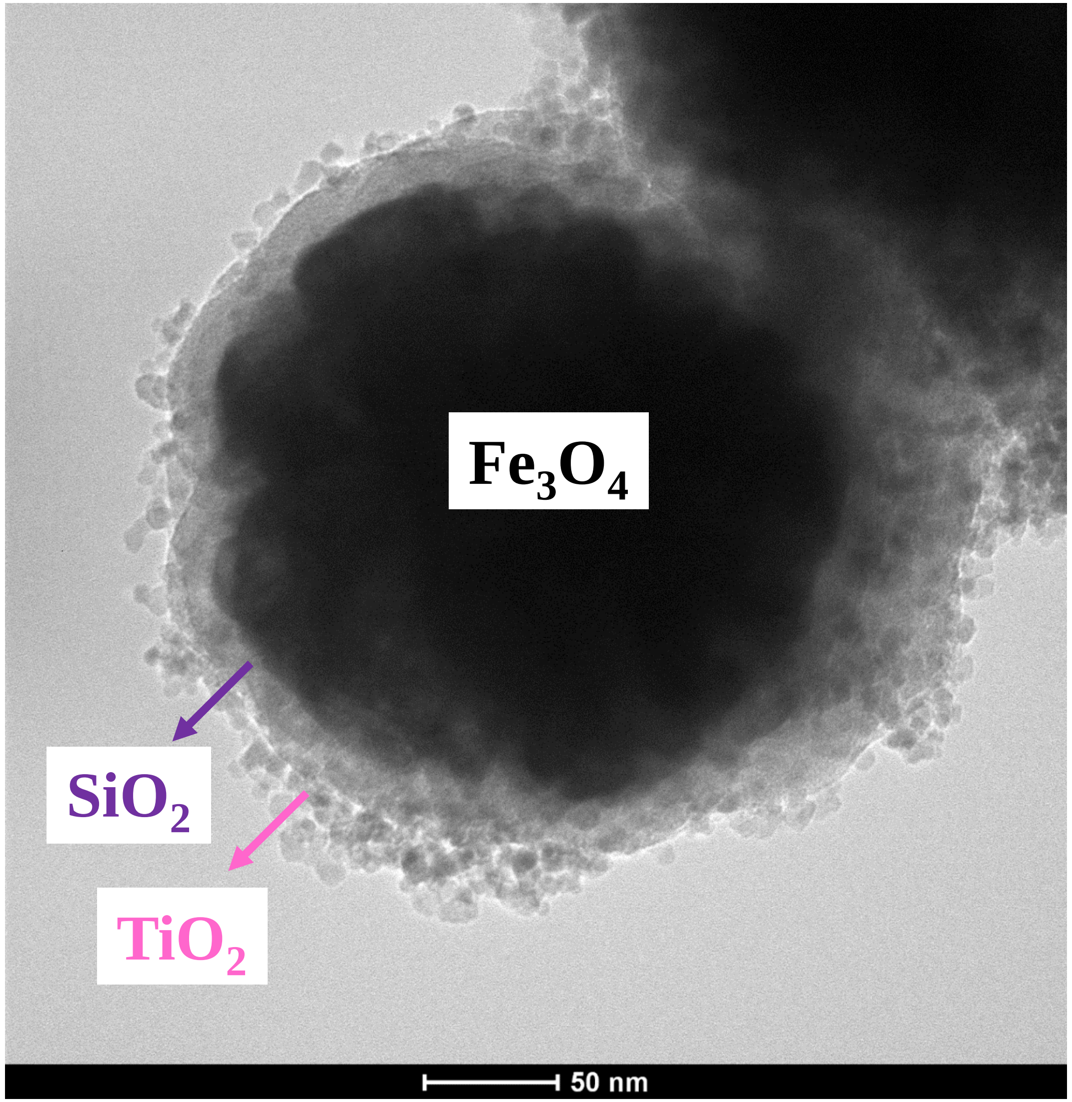


A2: Fe_3O_4@TiO_2



B2: Fe_3O_4@SiO_2@TiO_2





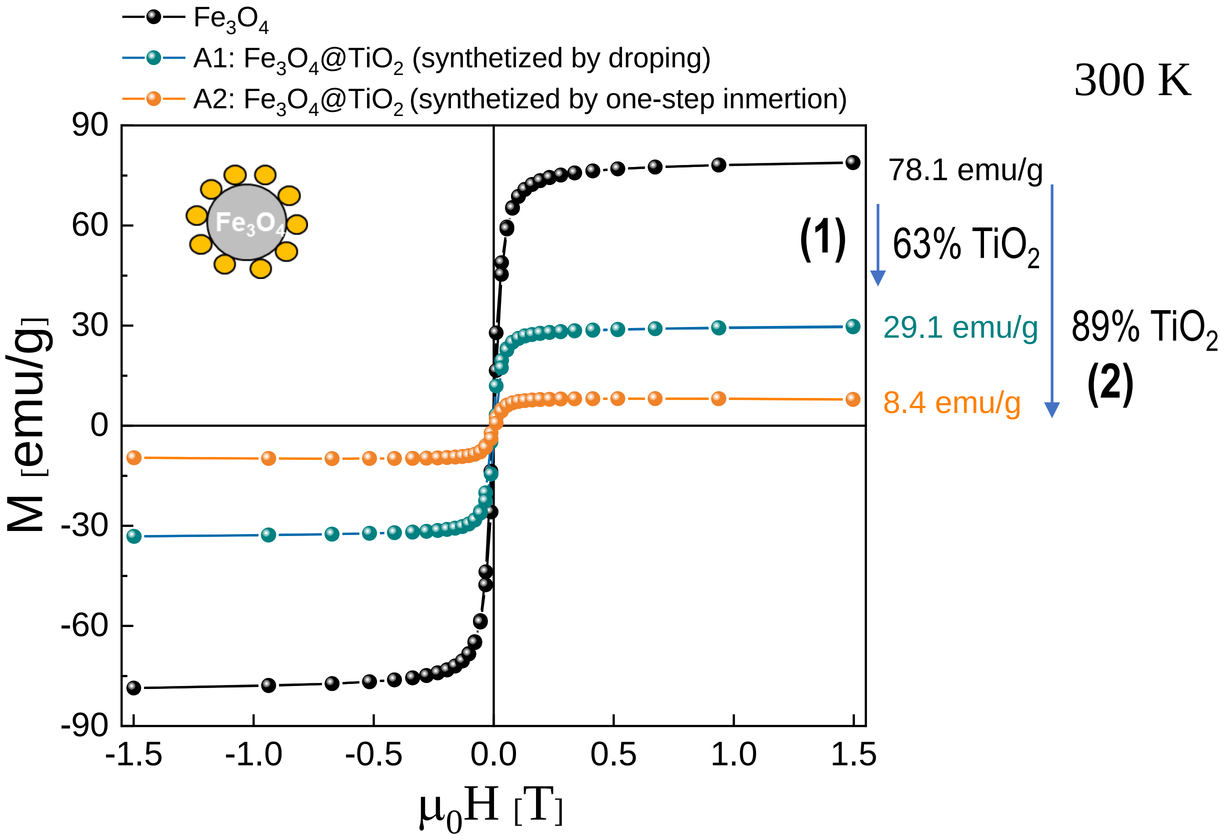
$Fe_3O_4@TiO_2$ NANOPARTICLES

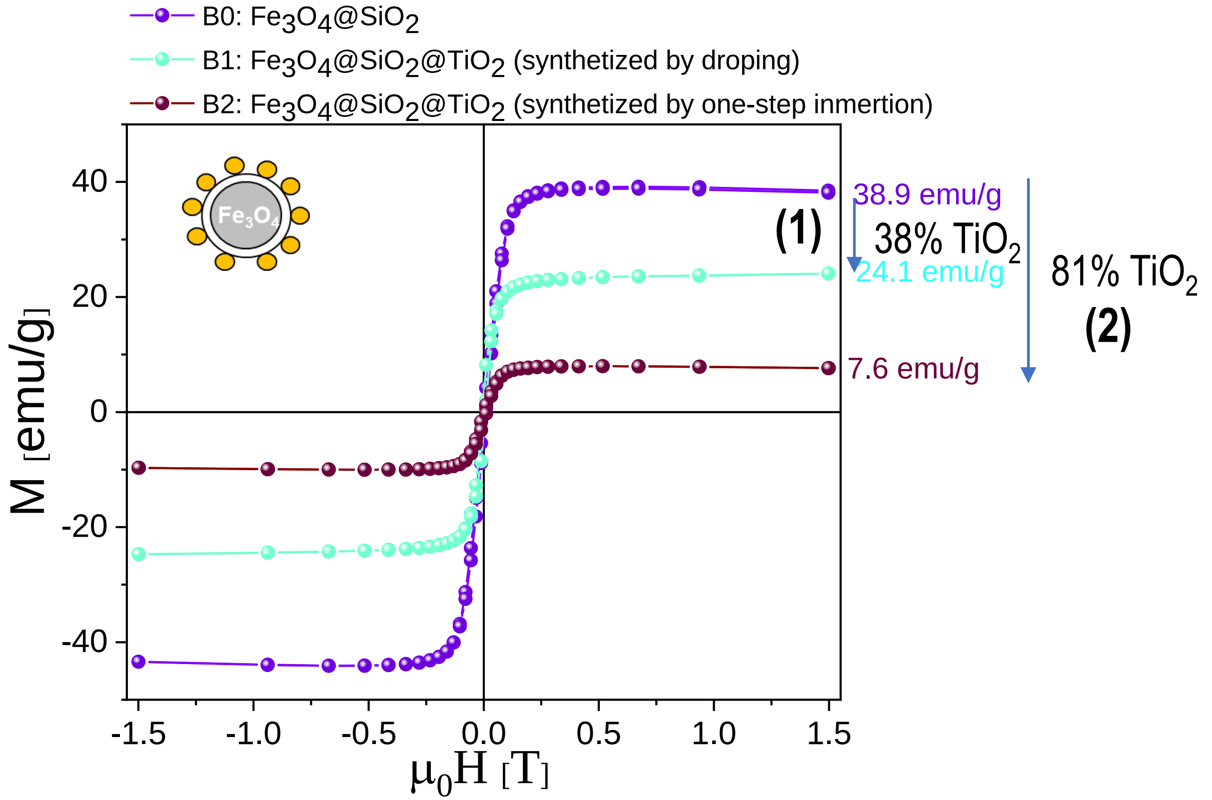
VSM

(2) WATER REMEDIATION

MAGNETIC CHARACTERIZATION

300 K



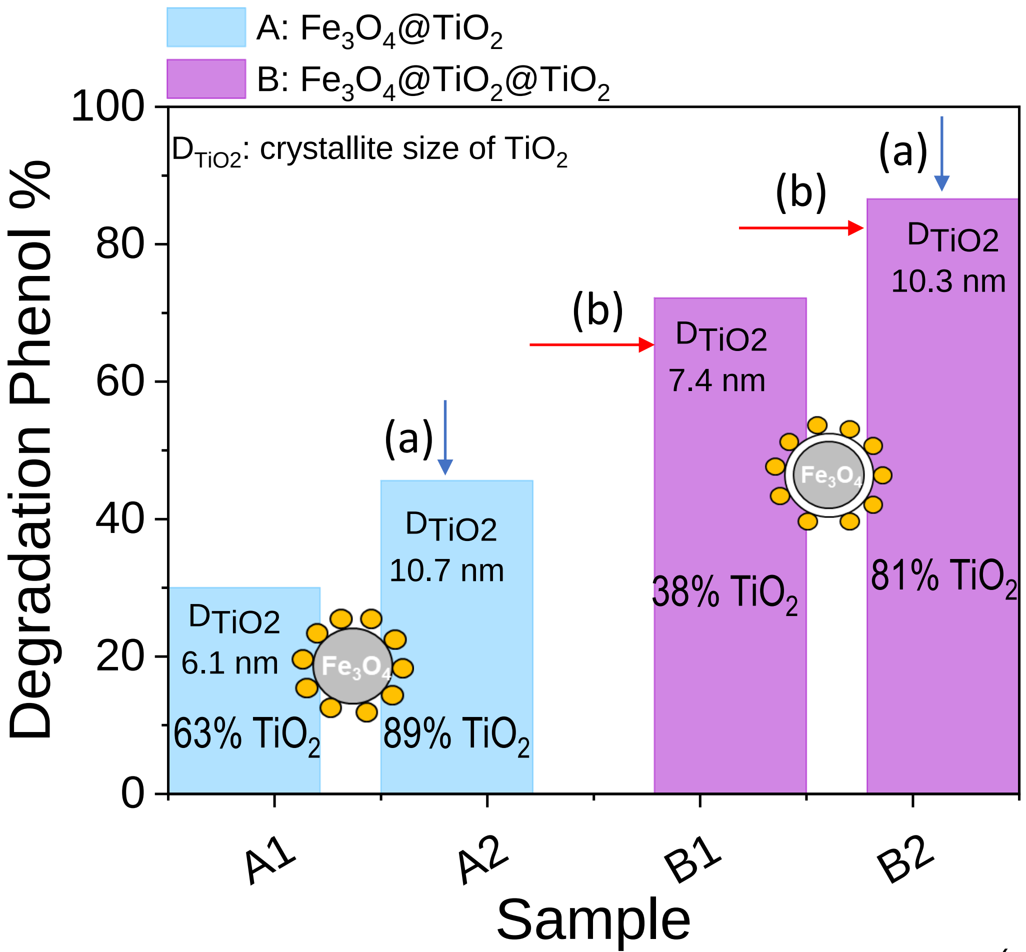


One-step (2) of TBOT provides a higher amount of TiO_2

$Fe_3O_4@TiO_2$ NANOPARTICLES

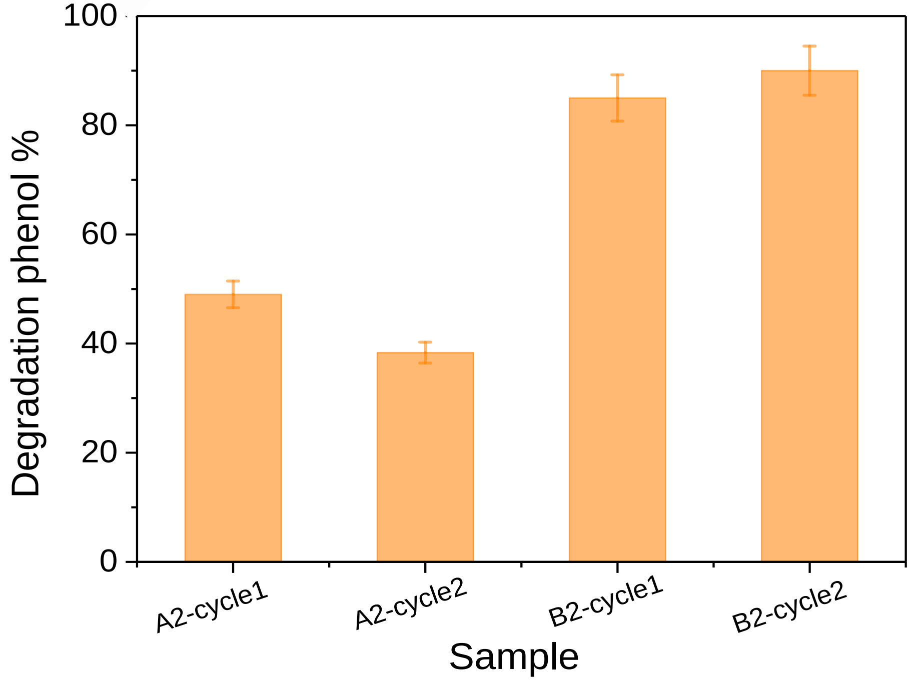
(2) WATER REMEDIATION

PHOTOCATALYTIC CHARACTERIZATION



$$Degradation\ Phenol\ \% = \frac{C(300\ min) - C_0}{C_0} \times 100$$

REUSE AND RECYCLING



(b) SiO_2 coating improves photocatalytic performance

(a) One-step immersion (2) of TBOT provides a higher photocatalytic degradation (higher % TiO_2 and larger crystallite size)

(2) WATER REMEDIATION

N-TiO_2 NANOPARTICLES

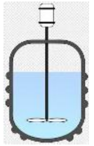
C. Gómez-Polo, L. Cervera-Gabalda, E. Garaio, J.J. Beato-López, J.I. Peréz-Landazábal, J. Environ. Chem. Eng.12, 5 (2024) 113643.

SYNTHESIS

solvothermal method

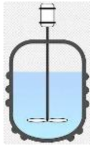
Y. C. Zhang *et al.,* Appl. Catal. B, 142–143 (2013) 249-258.

39mL of EtOH
+
0 – 2 mL HNO_3



10 min

+ 2.0 mL Ti (IV) butoxide



20 min

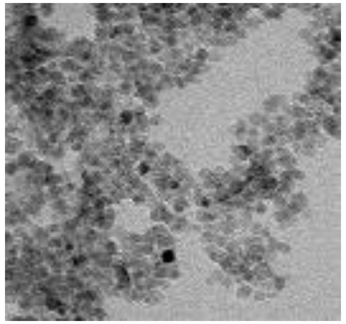
Teflon stainless steel autoclave

180 °C for 12 h

washing with EtOH
deionized water

Centrifugation

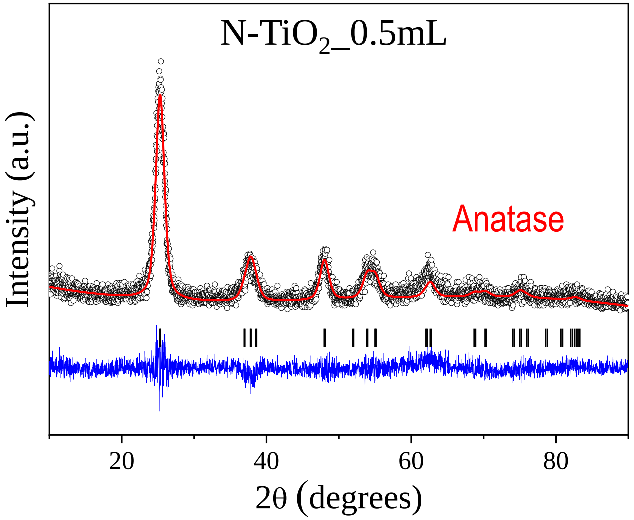
dried in vacuum at 100 °C for 4 h



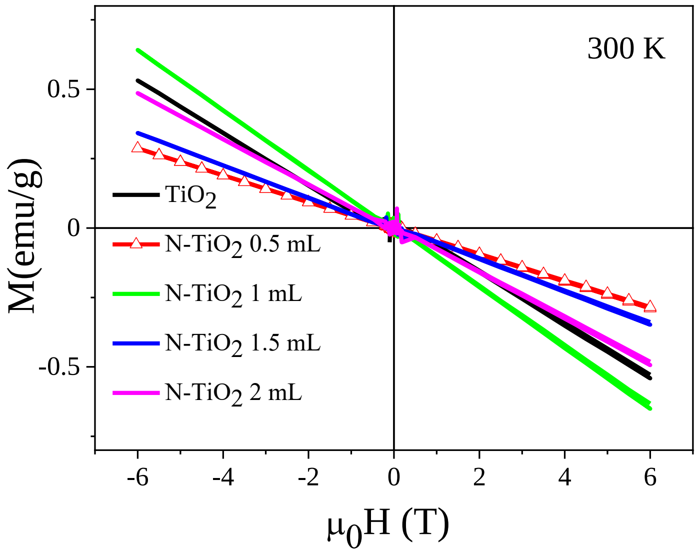
TEM

CHARACTERIZATION

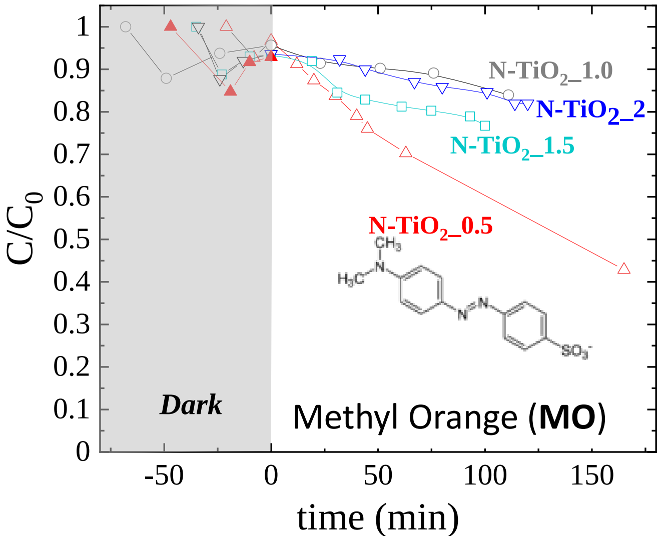
XRD



SQUID



PHOTOCATALYSIS



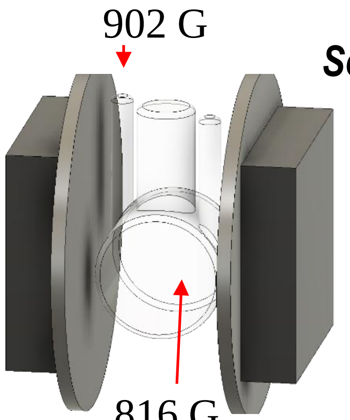
Xenon lamp

Visible
(400 nm cut-off filter)

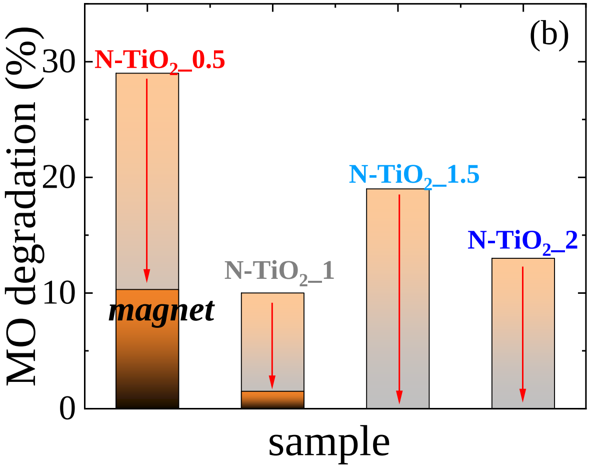
(2) WATER REMEDIATION

N-TiO$_2$ NANOPARTICLES

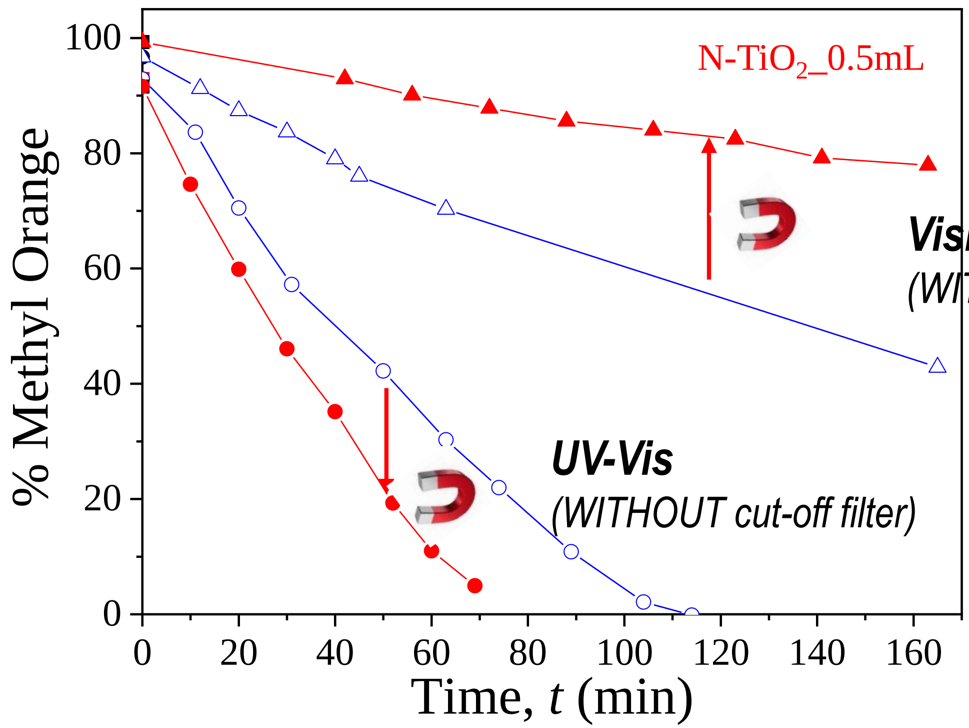
Effect of DC magnetic field on photocatalysis?



$\Delta B \approx 10\ \%$



Visible
(WITH cut-off filter)



Langmuir-Himshelwood model
for heterogeneous catalysis

$$v = -\frac{dC}{dt} = k_r \frac{k_a C}{1 + C}$$

k_a: adsoprtion constant
k_r: kinetic constant

$$k_{eff} = k_a k_r \qquad K_a C \ll 1$$

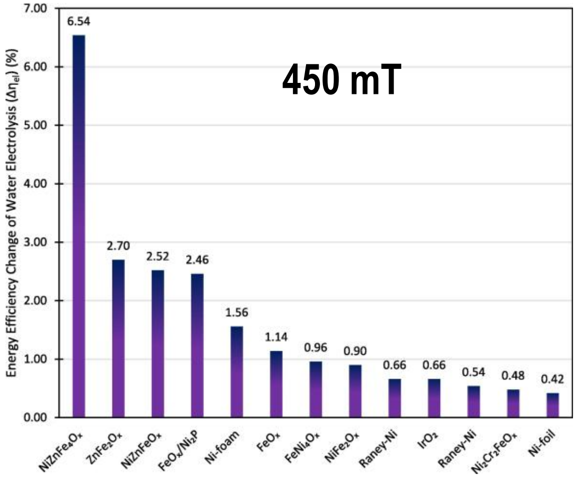
Sample	k_r (molL^{-1}min^{-1}) ×10^{-7}	K_a (Lmol^{-1}) ×10^{5}	k_r [+B] (molL^{-1}min^{-1})) ×10^{-7}	K_a [+B] (Lmol^{-1}) ×10^{5}
N-TiO$_2$_0.5	3.7	4.3	5.8	2.5
N-TiO$_2$_1.0	5.6	1.6	11.5	0.6

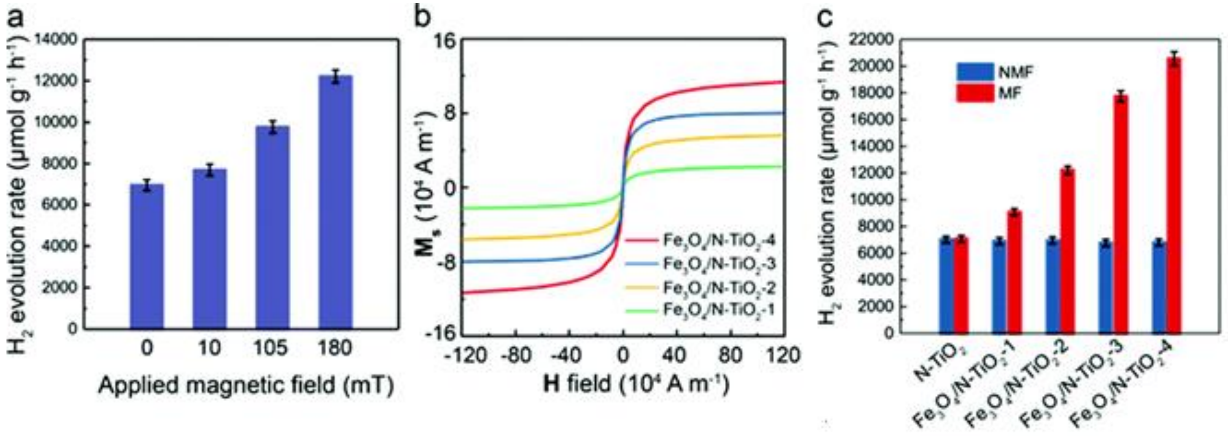
↑ Kinetic constant k_r
↓ Adsorption constant k_a

MAGNETIC FIELD EFFECTS

HYDROGEN PRODUCTION

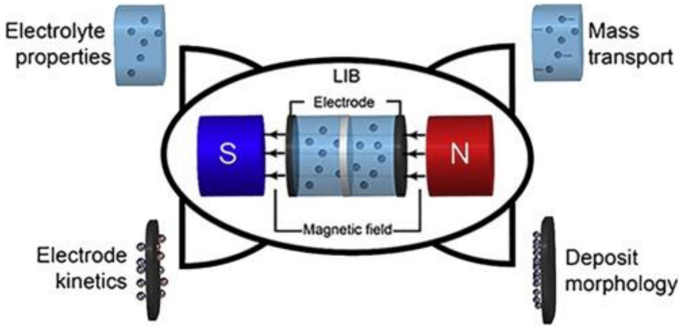
More efficient way of clean hydrogen production: The synergetic roles of magnetic effects and effective catalysts. Mert Temiz et al. *Fuel*, 376 (2024) 132708





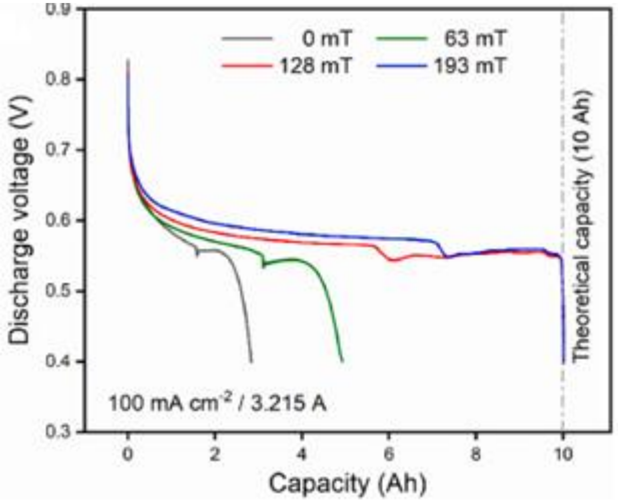
Local magnetic spin mismatch promoting photocatalytic overall water splitting with exceptional solar-to-hydrogen efficiency. Yiyang Li et al. *Energy Environ. Sci.*, 2022, 15, 265-277

BATTERIES



Magnetically active lithium-ion batteries towards battery performance improvement. Carlos M. Costa, et al. *iScience*, 24, 6 (2021) 102691

Enhancing capacity utilization of Li|LiCl-KCl-CsCl|Bi (300 °C) liquid metal batteries through the application of external magnetic fields, X. Zhou et al, *J. Power Sources* 624 (2024) 235516.



(2) WATER REMEDIATION

PHOTOCATALYSIS

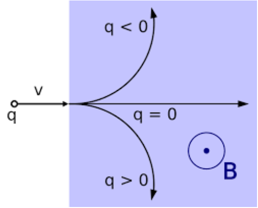
……. COMPLEX PHENOMENA

Research Advances in Magnetic Field-Assisted Photocatalysis.
R. Li et al. , *Adv. Funct. Mater.* , 34 (2024) 2316725.

Magnetic field effect on heterogeneous photocatalysis
H. Okumura et al., *Catalysis Today,* 258, Part 2, **2015**, 634-647.

LORENTZ FORCE decrease in the electron-hole recombination (charge separation)

$$\vec{F}_L = q\vec{v} \times \vec{B}$$



MHD (magneto-hydrodynamic) effect

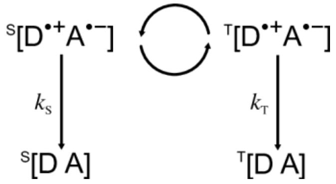
magnetic forces mainly act on paramagnetic species and molecules (i.e. dissolved oxygen)

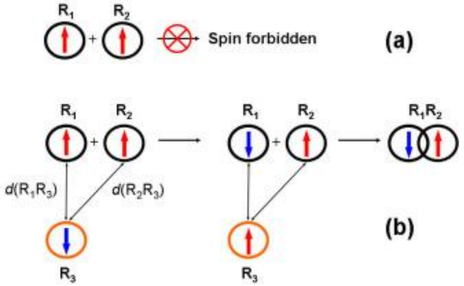
$$F = \frac{\chi}{\mu_0} B \frac{dB}{dz}$$

NON UNIFORM $\vec{B}$

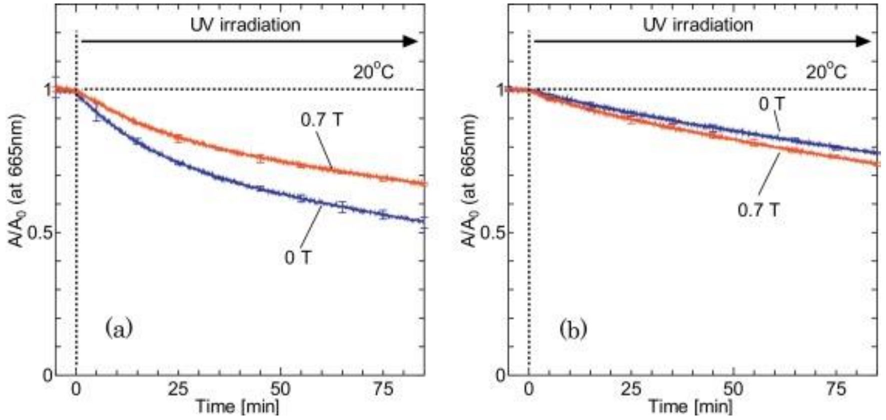
RADICAL PAIR mechanism

(Electron Spin Catalysis
A.L. Buchachenko, V.L. Berdinsky, *Chem. Rev.* **2002**, 102, 3, 603–612)





ADSORPTION/SURFACE STATE



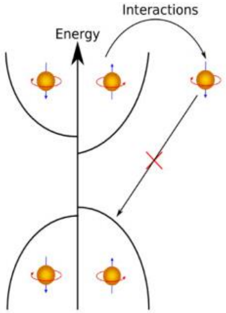
ZnO (a) dried, (b) moistened

(2) WATER REMEDIATION

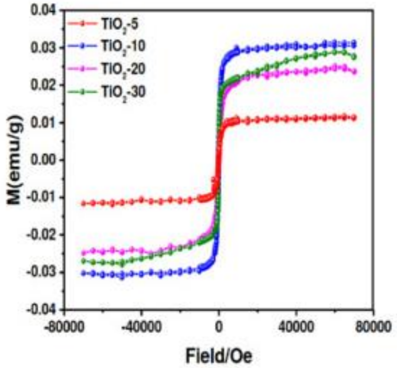
PHOTOCATALYSIS

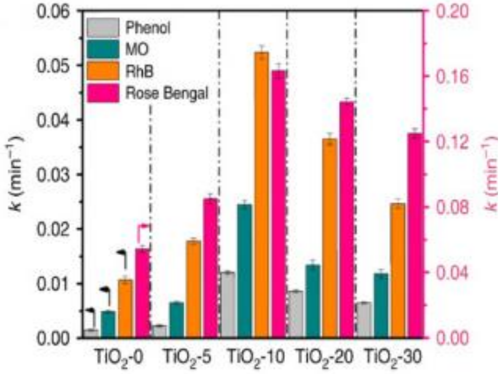
……. COMPLEX PHENOMENA

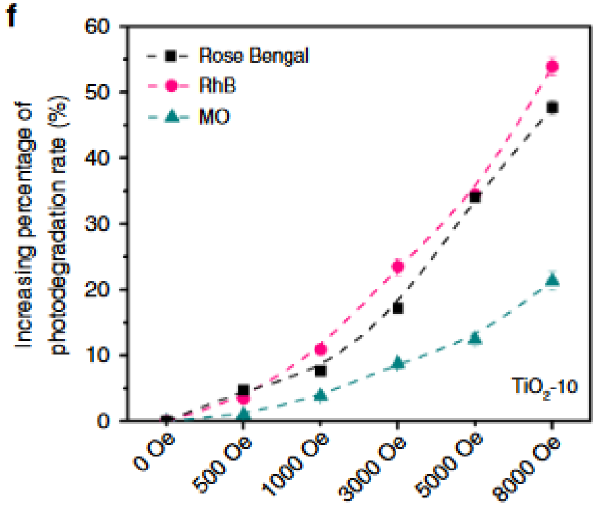
SPIN POLARIZATION photocatalyst



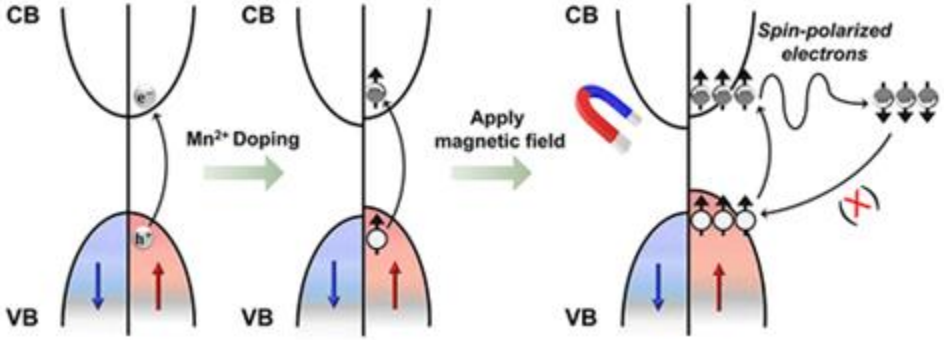
Manipulating spin polarization of titanium dioxide for efficient photocatalysis. L. Pan, *et al. Nat Commun* **11,** 418 (2020).



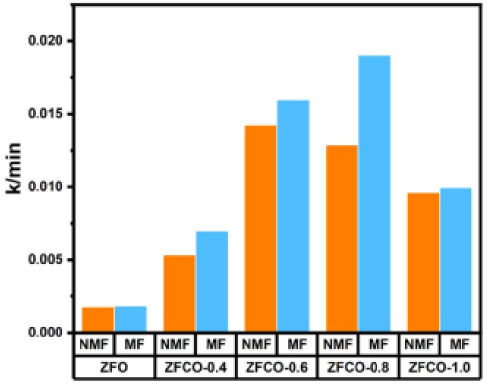




Spin-Polarized Photocatalytic CO_2 Reduction of Mn-Doped Perovskite Nanoplates, Cheng-Chieh Lin et al. *J. Am. Chem.* Soc., 144, 34 (2022) 15718–15726.



Manipulating spin-polarization of Co-doped $ZnFe_2O_4$ for photocatalytic TC degradation, Qijing Xie *et al J. Phys. D: Appl. Phys.* **57** (2024) 165104.



Acknowledgements

(2) WATER REMEDIATION

Combined photo and magnetic biocatalyst systems for tertiary treatment of emerging contaminants in wastewater (T3CE)

Gobierno de Navarra · Nafarroako Gobernua · AGENDA 2030

Asociación de la Industria Navarra

NILSA S.A. (Navarra de Infraestructuras Locales, S.A.)

Improved photocatalytic performance and environmental sustainability in water treatment processes using magnetic fields PID2020-116321RB-C21, funded by MCIN/AEI/ 10.13039/501100011033.

MINISTERIO DE CIENCIA E INNOVACIÓN · AGENCIA ESTATAL DE INVESTIGACIÓN

Sustainable photocatalytic nanostructures for environmental applications assisted by magnetic fields: water remediation and air quality monitoring (WARM)
PID2023-150078OB-I00, funded by MCIN/AEI/ 10.13039/501100011033.

MAGNETISM
&
Environmental Sustainability

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