Supporting Information

IRON OXIDE NANOCUBES ASSEMBLY ON SILVER NANOWIRE TEMPLATES TO ENHANCE MAGNETIC MAGNETIC HYPERTHERMIA PERFORMANCE

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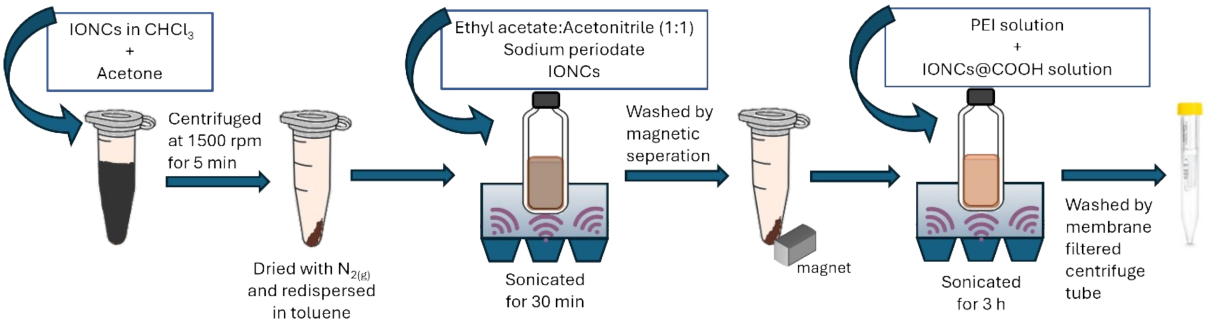

Scheme S1. Schematic view of the experimental procedure to surface functionalization IONCs with PEI.

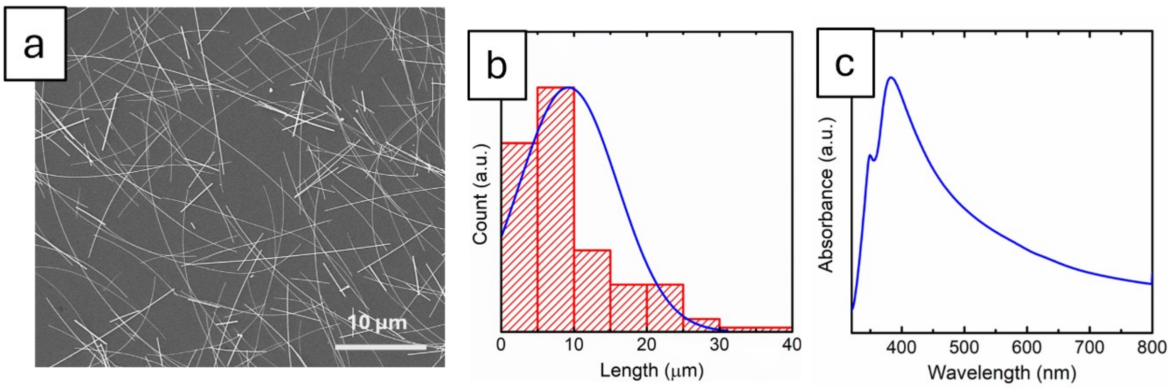

Figure S1. The SEM image (a), length size distribution graph (b), and the absorption spectrum (c) of the AgNWs. At least 100 number of AgNWs were measured for the statistic.

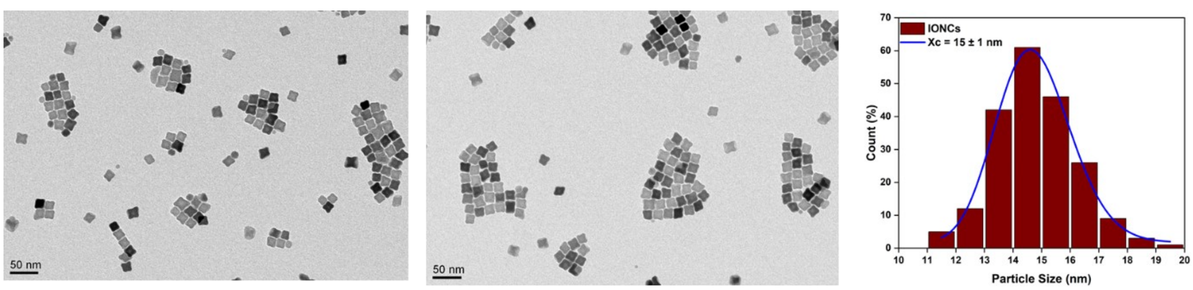

Figure S2. The particle size distribution of IONCs measured by statistical analysis on more than 200 objects selected from different TEM images.

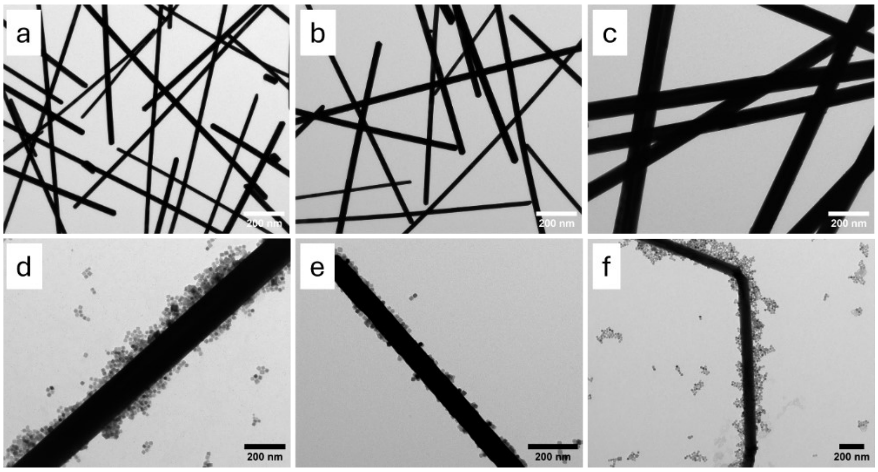

Figure S3. TEM images of re-synthesized AgNWs (a-c) and AgNWs@IONCs@PEI (d-f). The images demonstrate the reproducibility of our synthesis protocol in obtaining consistent morphologies across different batches.

Surface modification of IONCs with polydopamine

The surfaces of the IONCs (~12 nm) were modified with polydopamine (PD) via a ligand-exchange method. First, a 28 mM dopamine hydrochloride (DP.HCl) solution was prepared by dissolving DP.HCl in 3 mL of anhydrous dimethylformamide (DMF). Then, 0.0067 mL of triethylamine was added, and the mixture was vortex-mixed at 1200 rpm for 3 h at room temperature (RT). After this step, 0.150 mL of an IONCs in chloroform (2.85 $mg_{Fe}.mL^{-1}$) was added and the mixture was vortex-mixed overnight at RT. The resulting product was centrifuged at 1500 rpm for 5 min, the supernatant was discarded, and the particles were washed twice with DMF to remove excess reagents. The PD-coated nanoparticles (IONCs@PD) were then redispersed in water and further purified using centrifugal membrane filters (Millipore Sigma, Amicon membrane filters of 100kDa MWCO, 4 mL volume filter (Ultra-4)). The dispersions were centrifuged at 900 rpm for 5 min and replenished with fresh water. This washing step was repeated five times.

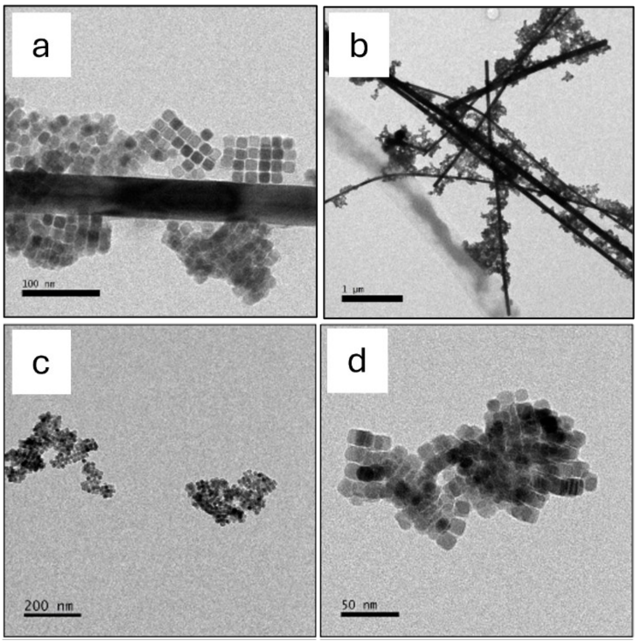

Figure S4. TEM images of AgNWs@IONCs@DP (a, b) and IONCs@PD (d,e) particles. The particle size distribution of IONCs@DP by intensity (c).

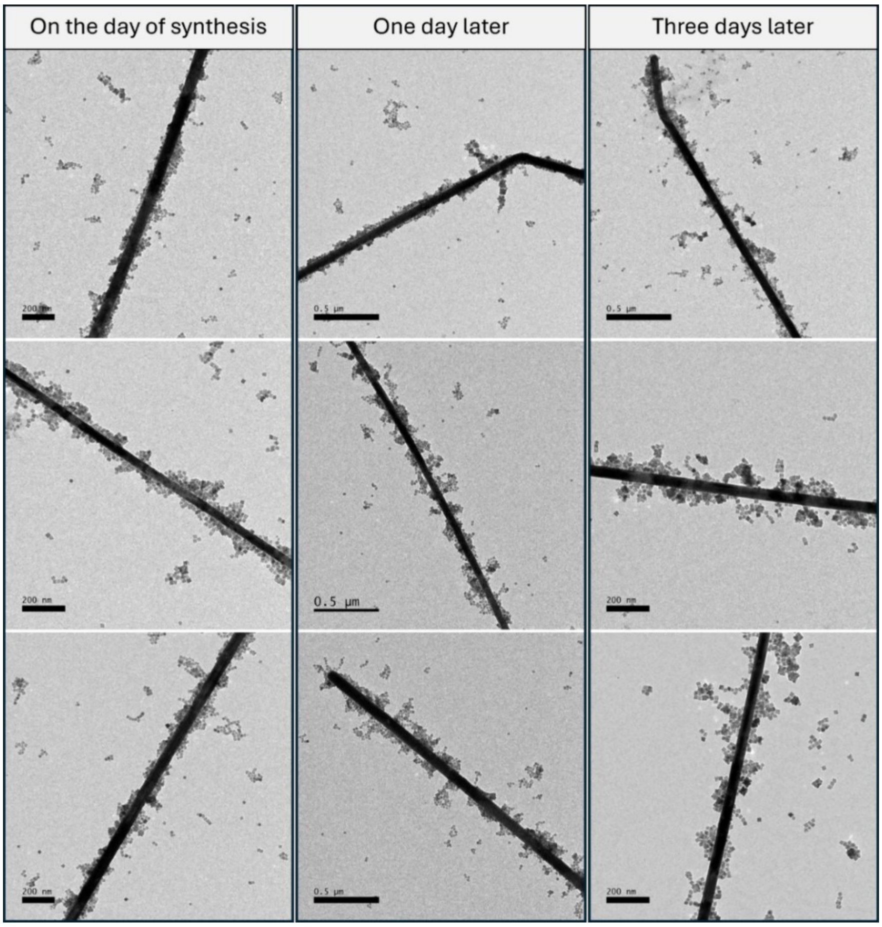

Figure S5. TEM images of AgNWs@IONCs@PEI composites over a three-day time. TEM images acquired immediately after synthesis (Day 0), after one day (Day 1), and after three days (Day 3).

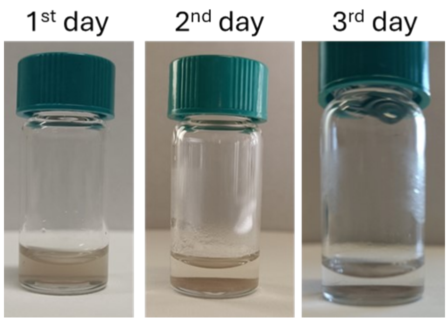

Figure S6. Photographs of the sample vials dispersed in water, showing the precipitation behavior of composites over time.

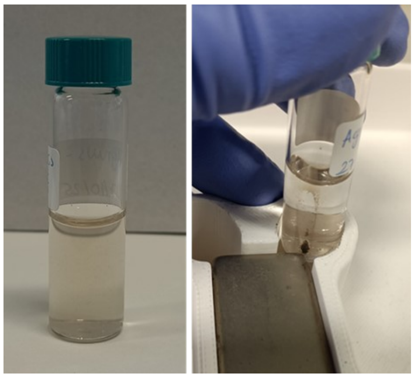

Figure S7. Typical photos of AgNWs@IONCs@PEI composites dispersion in water and after having kept them at the edge of a commercial permanent magnet (0.3T).

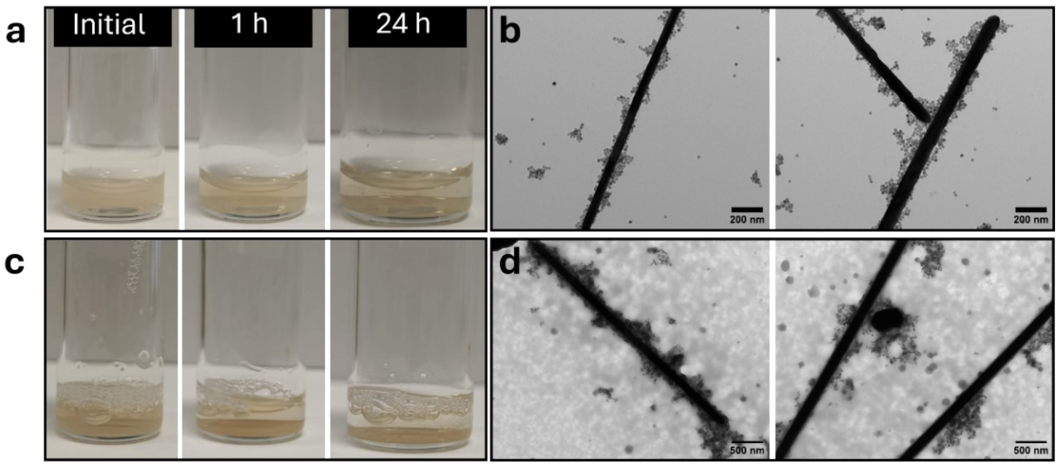

Figure S8. Photos of AgNws@IONCs@PEI composites dispersed in PBS (at pH 6.5) (a) or in DMEM supplemented with 10% of FBS (c), photos taken right after the dispersion, after 1 h, and after 24 h. TEM images of AgNws@IONCs@PEI composites dispersed in PBS (at pH 6.5) (b) or in DMEM supplemented with 10% of FBS (d), after incubation in these media for 24 h

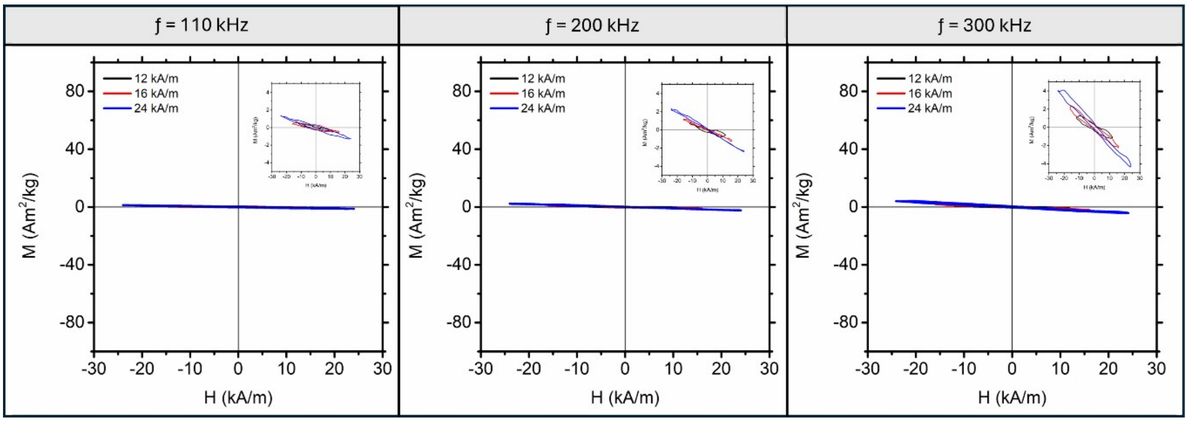

Figure S9. AC magnetometry measurements of AgNWs performed at different frequencies and magnetic field strength. The inset presents the corresponding magnetization curve on a reduced scale.

Surface modification of IONCs with citrate molecules

Surface modification with citrate molecules was implemented by following the reported protocols with some modifications. [1,2] 1ml of IONCs (16 nm) in Chloroform (5mgFe.mL-1) was mixed with 2 mL of aqueous solution of sodium Citrate (17.3 mM) to have a citrate molecule/surface area of IONCs ratio of 62 citrate ligand/nm2. The dispersion was shaken vigorously for 10-15 min and placed in a sonicator at 30-35˚C for 60 min. Next, 5 mL of acetone was added to the dispersion to accelerate the separation of IONCs@citrate with a permanent magnet. The IONCs, collected as a black pellet at the magnet, was redispersed in 2mL of water and washed at least 5 times by centrifugation at 1200 rpm for 10 min on membrane-filtered centrifuge tubes (Millipore Sigma, Amicon membrane filters of 100kDa MWCO, 4 mL volume filter (Ultra-4)).

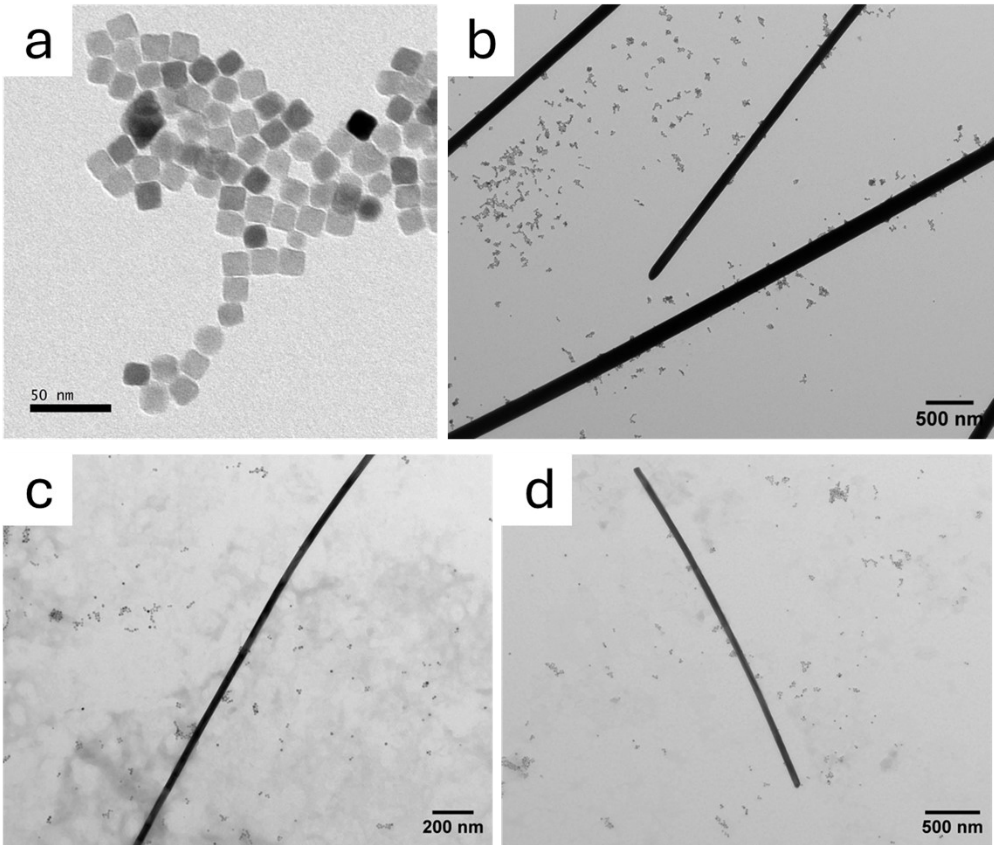

Figure S10. TEM images of IONCs@citrate (a) and Ag NWs with IONCs@citrate (AgNWs+IONCs@citrate) (b-d).

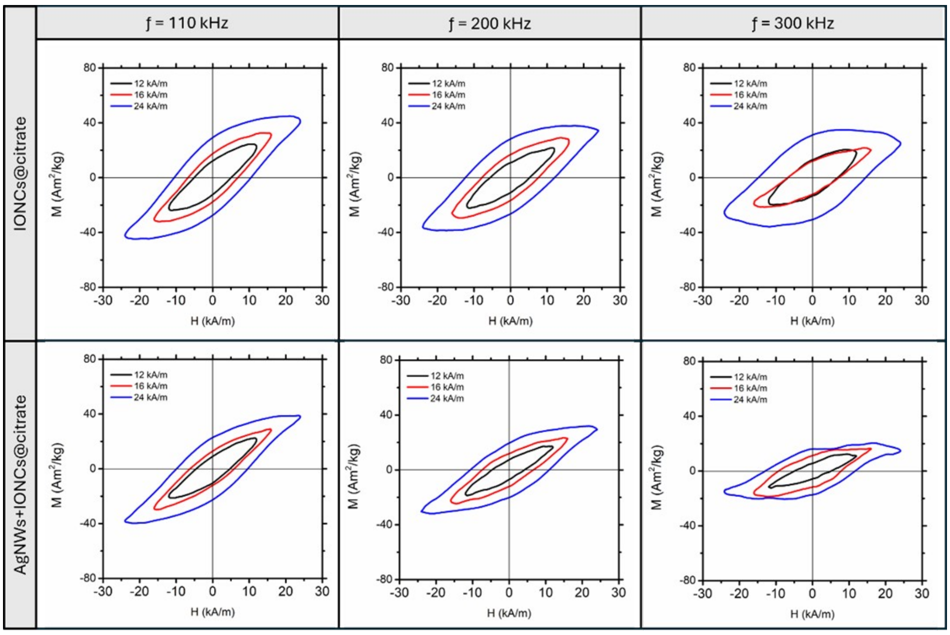

Figure S11. AC hysteresis loops of IONCs@citrate and AgNWs+IONCs@citrate under various frequencies and magnetic field strength. Each set of AC magnetometer measurements was repeated three times.

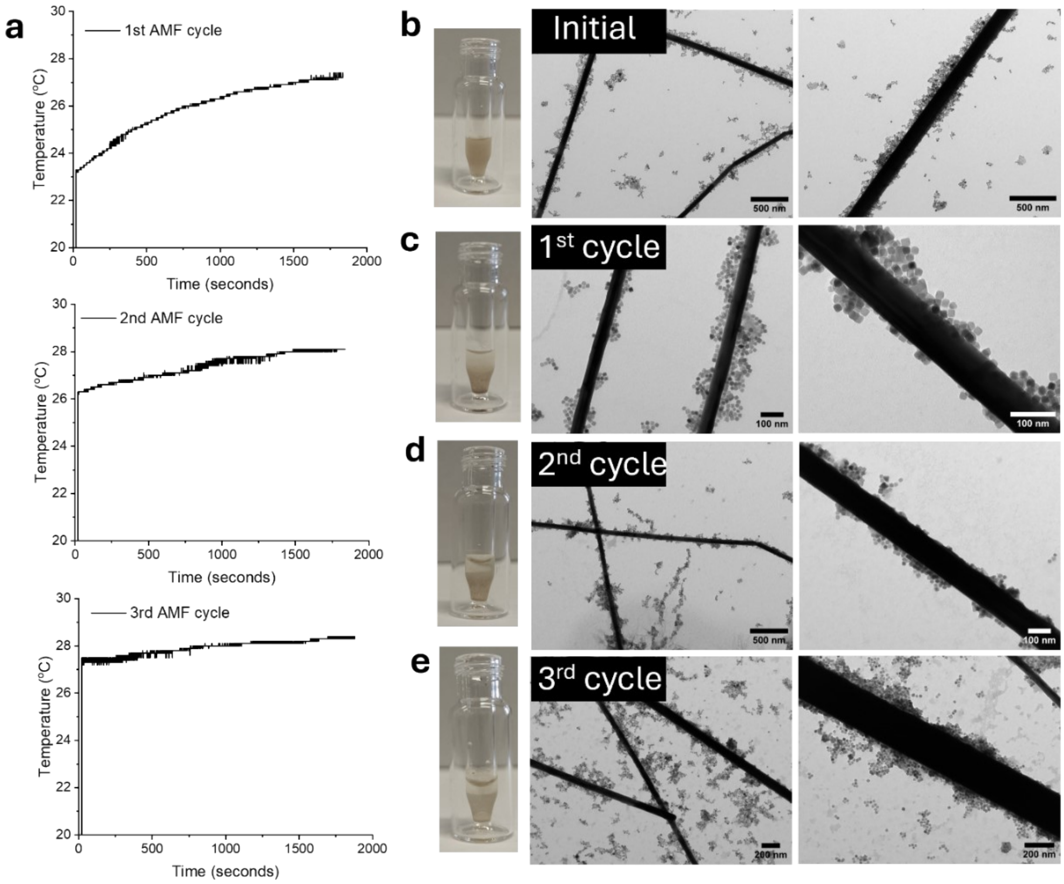

Figure S12. Heating profile of AgNWs@IONCs@PEI under AMF application at a frequency of 182 kHz and a field amplitude of 39 $kA.m^{-1}$ for each of the three cycles (a), Photograph of the sample dispersion and corresponding TEM images before AMF application (b) and after 1^{st}, 2^{nd}, and 3^{rd} cycle of AMF application, respectively (c-e).

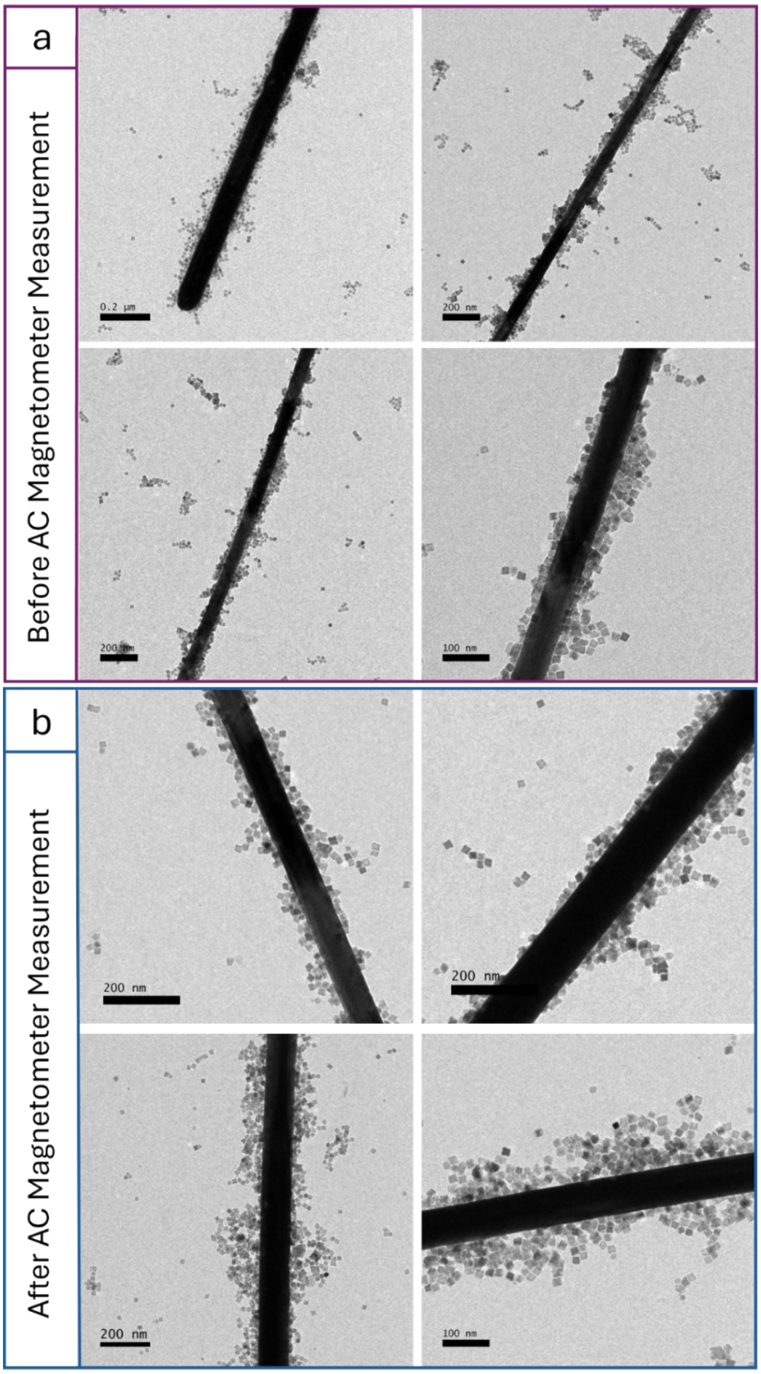

Figure S13. TEM images of the AgNWs@IONCs@PEI specimen before (a) and after (b) AC magnetometer measurement.

Tables

Table S1. Relative percentage change of H_c, M_s, area under the hysteresis loop (Area) and SAR values of samples.

Frequency (kHz)	**H_{app} ($kA.m^{-1}$)**	**ΔH_c (%)** (B/A)	**ΔH_c (%)** (C/B)	**ΔM_s (%)** (B/A)	**ΔM_s (%)** (C/B)	**ΔArea (%)** (B/A)	**ΔArea (%)** (C/B)	**ΔSAR (%)** (B/A)	**ΔSAR (%)** (C/B)
110	**12**	24,14	13,89	-26,07	-32,48	-13,93	-27,94	-13,48	-28,57
	16	27,78	28,26	-19,78	-26,05	-4,02	-7,28	-3,97	-8,26
	24	31,91	53,23	-18,18	-28,53	0,61	15,87	0,51	16,08
200	**12**	14,29	12,50	-27,52	-32,58	-20,00	-28,33	-20,11	-27,97
	16	16,67	38,78	-21,97	-35,92	-13,37	-9,69	-13,28	-9,91
	24	24,07	67,16	-17,49	-35,79	-3,72	18,00	-3,58	17,77
300	**12**	10,81	31,71	-27,84	-34,76	-24,53	-11,91	-24,35	-12,20
	16	18,60	39,22	-21,84	-33,08	-10,34	-5,40	-10,35	-5,47
	24	24,14	81,94	-16,71	-40,29	-2,76	17,79	-2,72	17,80

A=IONCs@COOH, B= IONCs@PEI, C= AgNWs@IONCs@PEI

B/A: Relative percentage change of IONCs@PEI compared to IONCs@COOH

C/B: Relative percentage change of AgNWs@IONCs@PEI compared to IONCs@PEI

Table S2. Results of one-way ANOVA (F(2,6)) and Tukey's post-hoc test comparing SAR mean values of IONCs@COOH, IONCs@PEI, and AgNWs@IONCs@PEI samples. Different Tukey group letters (i.e., a, b, and c) were assigned to samples that were statistically significantly different from each other.

Applied magnetic field condition		Sample	SAR ($W.g^{-1}_{Fe}$) Mean ± SD	n	Tukey Group ($p<0.05$)	One-way ANOVA F (2,6)	p-value
110 kHz	12 $kA.m^{-1}$	IONCs@COOH	88,90 ± 0,79	3	a	58,53	1.16×10^{-4}
		IONCs@PEI	76,50 ± 1,04	3	b		
		AgNWs@IONCs@PEI	55,13 ± 6,57	3	c		
	16 $kA.m^{-1}$	IONCs@COOH	125,57 ± 1,88	3	a	5,27	0,04777
		IONCs@PEI	120,53 ± 0,98	3	a,b		
		AgNWs@IONCs@PEI	111,73 ± 8,90	3	b		
	24 $kA.m^{-1}$	IONCs@COOH	197,83 ± 5,34	3	a	11,52	0,00882
		IONCs@PEI	199,07 ± 2,93	3	a		
		AgNWs@IONCs@PEI	230,53 ± 15,21	3	b		
200 kHz	12 $kA.m^{-1}$	IONCs@COOH	179,27 ± 1,96	3	a	27,56	$9,46 \times 10^{-4}$
		IONCs@PEI	143,37 ± 5,14	3	b		
		AgNWs@IONCs@PEI	102,80 ± 21,16	3	c		
	16 $kA.m^{-1}$	IONCs@COOH	256,27 ± 3,25	3	a	112,65	$1,75 \times 10^{-5}$
		IONCs@PEI	221,93 ± 0,25	3	b		
		AgNWs@IONCs@PEI	200,37 ± 7,27	3	c		
	24 $kA.m^{-1}$	IONCs@COOH	390,87 ± 12,53	3	a	27,39	$9,62 \times 10^{-4}$
		IONCs@PEI	376,43 ± 7,83	3	a		
		AgNWs@IONCs@PEI	444,27 ± 14,19	3	b		
300 kHz	12 $kA.m^{-1}$	IONCs@COOH	270,77 ± 3,09	3	a	53,24	$1,52 \times 10^{-4}$
		IONCs@PEI	204,47 ± 11,52	3	b		
		AgNWs@IONCs@PEI	180,17 ± 15,15	3	b		
	16 $kA.m^{-1}$	IONCs@COOH	366,53 ± 4,70	3	a	3,44	0,10125
		IONCs@PEI	328,73 ± 9,66	3	a		
		AgNWs@IONCs@PEI	310,90 ± 44,70	3	a		
	24 $kA.m^{-1}$	IONCs@COOH	573,00 ± 34,24	3	a	19,01	0,00253
		IONCs@PEI	589,17 ± 7,74	3	a		
		AgNWs@IONCs@PEI	675,10 ± 13,91	3	b		

n: The number of repeats of the measurement.

Tukey Group ($p<0.05$): If the sample groups are statistically significantly different from each other, they are assigned different Tukey group letters. If they share the same letter, it indicates that they are not statistically significantly different from each other.

p-value: $p<0.05$ means that at least one group of sample mean differs significantly.

Table S3. Results of one-way ANOVA (F(2,6)) and Tukey's post-hoc test comparing SAR mean differences between two sets of samples. Tukey's multiple comparison test determines which specific pairs of groups show significant differences. Significant values are indicated as 1 for pairs of samples that differ significantly from each other, and 0 for those that do not.

Applied magnetic field condition		Means Comparison Tukey Test	SAR Mean Diff.	p-value	Significant
110 kHz	12 kA.m^{-1}	IONCs@PEI - IONCs@COOH	-12,40	0,01816	1
		AgNWs@IONCs@PEI - IONCs@COOH	-33,77	$9{,}73 \times 10^{-5}$	1
		AgNWs@IONCs@PEI - IONCs@PEI	-21,37	0,00124	1
	16 kA.m^{-1}	IONCs@PEI - IONCs@COOH	-5,03	0,51272	0
		AgNWs@IONCs@PEI - IONCs@COOH	-13,83	0,04222	1
		AgNWs@IONCs@PEI - IONCs@PEI	-8,80	0,18348	0
	24 kA.m^{-1}	IONCs@PEI - IONCs@COOH	1,23	0,98607	0
		AgNWs@IONCs@PEI - IONCs@COOH	32,70	0,01293	1
		AgNWs@IONCs@PEI - IONCs@PEI	31,47	0,0154	1
200 kHz	12 kA.m^{-1}	IONCs@PEI - IONCs@COOH	-35,90	0,03029	1
		AgNWs@IONCs@PEI - IONCs@COOH	-76,47	$7{,}54 \times 10^{-4}$	1
		AgNWs@IONCs@PEI - IONCs@PEI	-40,57	0,01797	1
	16 kA.m^{-1}	IONCs@PEI - IONCs@COOH	-34,33	$2{,}37 \times 10^{-4}$	1
		AgNWs@IONCs@PEI - IONCs@COOH	-55,90	$1{,}43 \times 10^{-5}$	1
		AgNWs@IONCs@PEI - IONCs@PEI	-21,57	0,00293	1
	24 kA.m^{-1}	IONCs@PEI - IONCs@COOH	-14,43	0,35759	0
		AgNWs@IONCs@PEI - IONCs@COOH	53,40	0,00355	1
		AgNWs@IONCs@PEI - IONCs@PEI	67,83	0,00101	1
300 kHz	12 kA.m^{-1}	IONCs@PEI - IONCs@COOH	-66,30	$8{,}26 \times 10^{-4}$	1
		AgNWs@IONCs@PEI - IONCs@COOH	-90,60	$1{,}45 \times 10^{-4}$	1
		AgNWs@IONCs@PEI - IONCs@PEI	-24,30	0,08188	0
	16 kA.m^{-1}	IONCs@PEI - IONCs@COOH	-37,80	0,26535	0
		AgNWs@IONCs@PEI - IONCs@COOH	-55,63	0,09371	0
		AgNWs@IONCs@PEI - IONCs@PEI	-17,83	0,70375	0
	24 kA.m^{-1}	IONCs@PEI - IONCs@COOH	-16,17	0,65531	0
		AgNWs@IONCs@PEI - IONCs@COOH	85,93	0,00697	1
		AgNWs@IONCs@PEI - IONCs@PEI	102,10	0,00295	1

Table S4. Results of one-way ANOVA (F(1,4)) and Tukey's post-hoc test comparing H_c mean values of IONCs@PEI and AgNWs@IONCs@PEI samples.

Applied magnetic field condition		Sample	H_c Mean ± SD	n	Tukey Group ($p<0.05$)	One-way ANOVA F (1,4)	p-value
110 kHz	12 kA.m^{-1}	IONCs@PEI	3,63 ± 0,06	3	a	2,19	0,2126
		AgNWs@IONCs@PEI	4,07 ± 0,5	3	a		
	16 kA.m^{-1}	IONCs@PEI	4,57 ± 0,06	3	a	98,88	5,74363 x 10^{-4}
		AgNWs@IONCs@PEI	5,93 ± 0,23	3	b		
	24 kA.m^{-1}	IONCs@PEI	6,20 ± 0,00	3	a	784,69	9,73421 x 10^{-6}
		AgNWs@IONCs@PEI	9,57 ± 0,21	3	b		
200 kHz	12 kA.m^{-1}	IONCs@PEI	4,03 ± 0,06	3	a	2,81	0,16884
		AgNWs@IONCs@PEI	4,53 ± 0,51	3	a		
	16 kA.m^{-1}	IONCs@PEI	4,93 ± 0,06	3	a	605,00	1,62404 x 10^{-5}
		AgNWs@IONCs@PEI	6,77 ± 0,12	3	b		
	24 kA.m^{-1}	IONCs@PEI	6,63 ± 0,06	3	a	2278,13	1,19597 x 10^{-6}
		AgNWs@IONCs@PEI	11,13 ± 0,15	3	b		
300 kHz	12 kA.m^{-1}	IONCs@PEI	4,10 ± 0,10	3	a	29,82	0,00547
		AgNWs@IONCs@PEI	5,40 ± 0,40	3	b		
	16 kA.m^{-1}	IONCs@PEI	5,13 ± 0,06	3	a	11,92	0,02599
		AgNWs@IONCs@PEI	7,10 ± 0,98	3	b		
	24 kA.m^{-1}	IONCs@PEI	7,16 ± 0,25	3	a	106,32	4,9915 x 10^{-4}
		AgNWs@IONCs@PEI	13,10 ± 0,96	3	b		

Table S5. Results of one-way ANOVA ($F(1,4)$) and Tukey's post-hoc test comparing H_c mean values of IONCs@citrate and AgNWs+IONCs@citrate samples. Each set of AC magnetometer measurements was repeated three times.

Applied magnetic field condition		Sample	H_c Mean ± SD	n	Tukey Group ($p<0.05$)	One-way ANOVA F (1,4)	p-value
110 kHz	12 kA.m^{-1}	IONCs@citrate	5,07 ± 0,55	3	a	0,75	0,43423
		AgNWs+IONCs@citrate	4,67 ± 0,58	3	a		
	16 kA.m^{-1}	IONCs@citrate	6,8 ± 0,46	3	a	4,00	0,11612
		AgNWs+IONCs@citrate	6,0 ± 0,52	3	a		
	24 kA.m^{-1}	IONCs@citrate	10,53 ± 0,50	3	a	5,38	0,08112
		AgNWs+IONCs@citrate	9,73 ± 0,32	3	a		
200 kHz	12 kA.m^{-1}	IONCs@citrate	5,47 ± 0,57	3	a	9,24	0,03841
		AgNWs+IONCs@citrate	4,43± 0,15	3	b		
	16 kA.m^{-1}	IONCs@citrate	7,70 ± 0,75	3	a	0,55	0,50005
		AgNWs+IONCs@citrate	7,00 ± 1,45	3	a		
	24 kA.m^{-1}	IONCs@citrate	12,27 ± 0,76	3	a	6,71	0,06072
		AgNWs+IONCs@citrate	10,77 ± 0,65	3	a		
300 kHz	12 kA.m^{-1}	IONCs@citrate	270,77 ± 3,09	3	a	1,09	0,35536
		AgNWs+IONCs@citrate	204,47 ± 11,52	3	a		
	16 kA.m^{-1}	IONCs@citrate	7 ± 1,01	3	a	4,18	0,11036
		AgNWs+IONCs@citrate	8,67 ± 0,98	3	a		
	24 kA.m^{-1}	IONCs@citrate	14,47 ± 3,04	3	a	1,29	0,31902
		AgNWs+IONCs@citrate	12,3 ± 1,28	3	a		

Table S6. Results of one-way ANOVA ($F(1,4)$) and Tukey's post-hoc test comparing SAR mean values of IONCs@citrate and AgNWs+IONCs@citrate samples. Each set of AC magnetometer measurements was repeated three times.

Applied magnetic field condition		Sample	SAR ($W.g^{-1}_{Fe}$) Mean ± SD	n	Tukey Group ($p<0.05$)	One-way ANOVA F (1,4)	p-value
110 kHz	12 kA.m^{-1}	IONCs@citrate	56,63 ± 5,16	3	a	10,61	0,03117
		AgNWs+IONCs@citrate	44,00 ± 4,30	3	b		
	16 kA.m^{-1}	IONCs@citrate	101,93 ± 10,52	3	a	12,23	0,02495
		AgNWs+IONCs@citrate	73,57 ± 9,30	3	b		
	24 kA.m^{-1}	IONCs@citrate	230,20 ± 16,71	3	a	20,62	0,01049
		AgNWs+IONCs@citrate	179,07 ± 10,06	3	b		
200 kHz	12 kA.m^{-1}	IONCs@citrate	91,97 ± 4,72	3	a	45,68	0,0025
		AgNWs+IONCs@citrate	61,20 ± 6,32	3	b		
	16 kA.m^{-1}	IONCs@citrate	182,53 ± 24,53	3	a	4,61	0,09818
		AgNWs+IONCs@citrate	130,80 ± 33,74	3	a		
	24 kA.m^{-1}	IONCs@citrate	412,77 ± 30,86	3	a	16,92	0,01469
		AgNWs+IONCs@citrate	292,83 ± 39,97	3	a		
300 kHz	12 kA.m^{-1}	IONCs@citrate	169,23 ± 24,77	3	a	12,18	0,02512
		AgNWs+IONCs@citrate	73,17 ± 40,74	3	b		
	16 kA.m^{-1}	IONCs@citrate	190,70 ± 52,04	3	a	0,02	0,88487
		AgNWs+IONCs@citrate	185,13 ± 34,62	3	a		
	24 kA.m^{-1}	IONCs@citrate	704,30± 298,37	3	a	3,70	0,12691
		AgNWs+IONCs@citrate	347,17 ± 120,44	3	a		

References

(1) Vassallo, M., Martella, D., Barrera, G., Celegato, F., Coïsson, M., Ferrero, R., ... & Manzin, A. (2023). Improvement of hyperthermia properties of iron oxide nanoparticles by surface coating. *ACS omega*, *8*(2), 2143-2154.

(2) Arndt, D., Gesing, T. M., & Bäumer, M. (2012). Surface functionalization of iron oxide nanoparticles and their stability in different media. *ChemPlusChem*, *77*(7), 576-583.