SUPPLEMENTARY INFORMATION

Quality of physicochemical data on nanomaterials: an assessment of data completeness and variability

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S1. Selection procedure of physicochemical properties in GRACIOUS

The GRACIOUS consortium selected 14 nanomaterial physicochemical properties after examining documents that have relevance in the context of REACH, namely: legal text and revised Annexes with requirements for identification and registration of nanoforms; and dedicated guidance published by ECHA with recommendations on how to address specific endpoints in the case of nanomaterials and how to apply grouping and read-across concepts to nanoforms. In particular, nine physicochemical properties were proposed in the project work plan (Composition, Crystallinity, Particle size, Particle Shape, Surface chemistry, Specific surface area, Density, Surface charge, Surface hydrophobicity) and confirmed via crosschecking with those recommended in the documents. Five more properties (Water solubility and dissolution rate, Dispersibility, Dustiness, Biological (re)activity and Photoreactivity) were added to the final list based on their relevance for grouping and read-across.

Documents crosschecked

[1] Revised Annexes to REACH with specific provisions for nanoforms: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.308.01.0001.01.ENG&toc=OJ:L:2018:308:TOC
[2] ECHA Appendix for nanomaterials applicable to the endpoint-specific guidance on information requirements: https://echa.europa.eu/documents/10162/13632/appendix_r7a_nanomaterials_en.pdf/1bef8a8a-6ffa-406a-88cd-fd800ab163ae
[3] ECHA Appendix for nanomaterials to the guidance on grouping of chemicals: https://echa.europa.eu/documents/10162/23036412/appendix_r6_nanomaterials_en.pdf/71ad76f0-ab4c-fb04-acba-074cf045eaaa

Table S1 shows the 14 nanomaterial physicochemical properties that were considered relevant for the GRACIOUS project and their occurrence in the three documents with regulatory relevance for REACH. Dispersibility, Biological (re)activity, and Photoreactivity were not addressed in the present study as they will be tackled at a later stage of the project.

Table S1. Comparison between GRACIOUS Description of Work and three documents with regulatory relevance for REACH on the recommended physicochemical properties for nanoform identification, characterisation and grouping.

[1] https://eur-lex.europa.eu/eli/reg/2018/1881/oj
[3] https://echa.europa.eu/documents/10162/13632/appendix_r7a_nanomaterials_en.pdf/1bef8a8a-6ffa-406a-88cd-fd800ab163ae
[2] https://echa.europa.eu/documents/10162/23036412/appendix_r6_nanomaterials_en.pdf
[#] *'Surface functionalisation or treatment and identification of each agent' is the REACH information requirement which is closest to the concept of 'chemical nature of the surface' mentioned in the GRACIOUS Description of Work.*
[*] *'Partitioning coefficient n-octanol/water' is the REACH information requirement which is closest to the concept of 'hydrophobicity' mentioned in the GRACIOUS Description of Work and ECHA Guidance.*
[§] *'Oxidative properties' is the REACH information requirement which is closest to the concept of 'photoreactivity' mentioned in ECHA Guidance.*

Nomenclature adopted in this study	**Nomenclature adopted in documents**	**GRACIOUS Description of Work**	**REACH Annexes 2018 Update**	**ECHA Guidance 2017 Endpoints**	**ECHA Guidance 2017 Grouping**
List of all physicochemical properties as mentioned in this study	*List of all physicochemical properties as mentioned in the documents that were consulted (and are specified in next columns)*	*Properties to be acquired (from existing databases or testing) for the project case studies (Group 1 and 2 materials)*	*Nanospecific provisions in identification (Annex VI, point 2.4) and standard information requirements (Annex VII-IX)*	*Recommendations for nanomaterials on information requirements for substance registration under REACH (regardless tonnage)*	*Key physicochemical properties that may be possibly relevant for grouping and read-across of nanoforms under REACH*
Composition	Composition	X	X		X
	Impurities	X	X		X
	Assembly structure		X		
	Ion content of suspension	X			
Crystallinity	Cristallinity	X	X		X
Particle size	Particle size	X	X	X	X
	Agglomeration/aggregation			X	X
Dustiness	Dustiness		X	X	X
Particle shape	Shape	X	X	X	X
	Aspect ratio		X		
	Rigidity and hardness				X
Surface chemistry	Chemical nature of the surface	X	X[#]		X

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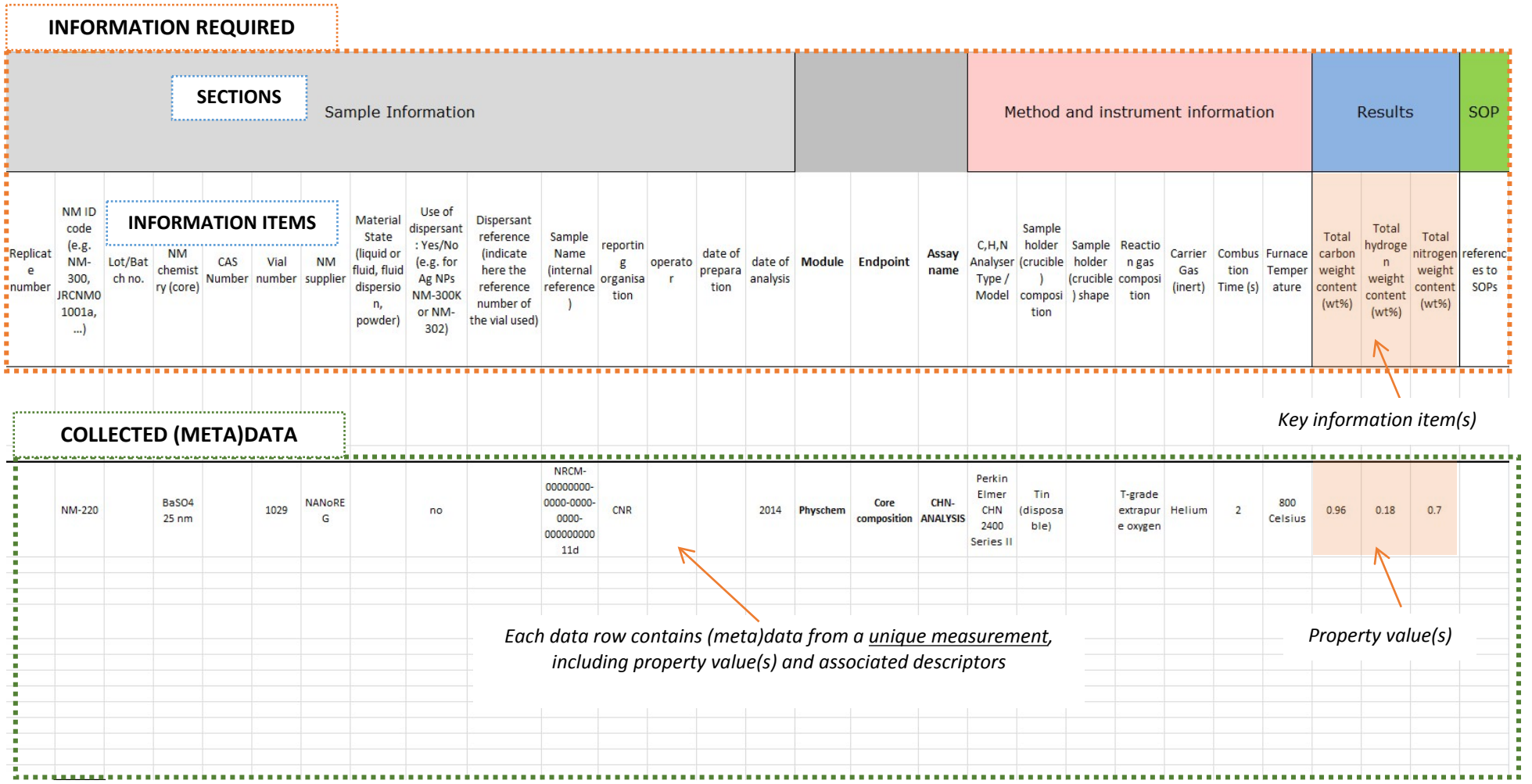
Specific surface area	Specific surface area by volume or mass	X	X	X	X
Density	Density	X			
Surface charge	Surface charge	X			X
Surface hydrophobicity	Hydrophobicity	X	X*	X*	X
	Attachment, removal and sorption			X	
Water solubility and dissolution rate	Water solubility incl. dissolution rate in water and relevant biological and environmental media		X	X	X
Dispersibility	Dispersibility		X	X	X
Biological (re)activity	Biological or surface reactivity (ROS)				X
Photoreactivity	Photoreactivity				X

S2. Structure of GRACIOUS templates

Figure S2. GRACIOUS template used for structuring the data obtained from the technique *CHN analysis* (property: *Composition*) and to assess their completeness.



S3. Key information items and property values driving data selection

In this study, the "key" information items are included in the columns of the templates and represent the specific information (measurand) on the results obtained from the application of the measurement technique. Key information items differ depending on the technique. (Meta)data collected under these columns are called "property values". Only data rows reporting at least one property value were selected in the study. Those without at least one property value were discarded. Table S3 lists the key information items for each technique considered. More than one information item was selected if the application of the corresponding technique leads to more than one outcome.

Table S3. Key information items for each technique considered in the study.

Technique	Key information items	Technique	Key information items	Technique	Key information items
ATR-FTIR	Functional groups	**Filtration +ICP-MS**	analyte concentration (ng/mL) corrected for dilutions and blank	**Surface energy**	Overall surface energy (mN/m)
BET analysis	S_{BET} (m^2/g)	**GC-MS**	Identified compounds	**TEM-size**	ECD mean
			Semi-quantitative amount (%MNM mass)		Feret min mean
CHN analysis	Total C weight content (wt%)	**ICP-MS**	Element	**TEM-shape**	Aspect ratio - mean
	Total H weight content (wt%)		Concentration of element in the sample (mg/kg)		Solidity - mean
	Total N weight content (wt%)				
CLS	Mass weighted mean diameter (nm)	**ICP-OES**	Element	**TGA functional groups**	Weight loss (%)
			Concentration of element (mg/kg)		
Density (Pycnometry)	Density (g/cm^3)	**ELS (IEP)**	IEP (+/- 0,01 pH unit)	**TGA mass of coating**	Water: weight loss, mean(%)
					Associated organics: mean weight loss(%)
DLS	Z-ave hydrodynamic diameter (nm)	**LC-MS**	Detected/Identified compounds	**Water contact angle**	Contact angle (θ)
			Semi-quantitative amount (%MNM mass)		
Dustiness - other set-up	Dustiness index in respirable number (1/mg)	**MALDI-TOF**	Polymer detected/ identified	**XPS**	Surface composition (%)
Dustiness - small drum	Dustiness index in respirable number (1/mg)	**PLE**	Appearance of the extract	**XRD - crystalline phase**	Crystalline phases and percentages
EDX	Elemental composition %	**Sears titration**	specific surface area (m2/g)	**XRF**	Analyte
					Concentration of analyte in the sample (%)
Density (Other set-up)	effective density (g/cm^3)	**sp-ICP-MS**	Particle size distribution Mean/mode [nm]/ [nm]	**ELS (Z-potential)**	Zeta potential (mV)
ES-DMA	Mean diameter (number weighted) (nm)	**STEM-EDS**	Calculation of Atomic Percentage of surface coating		
			Absolute Quantification of surface coating		

S4 Procedure of data collection from Gracious database

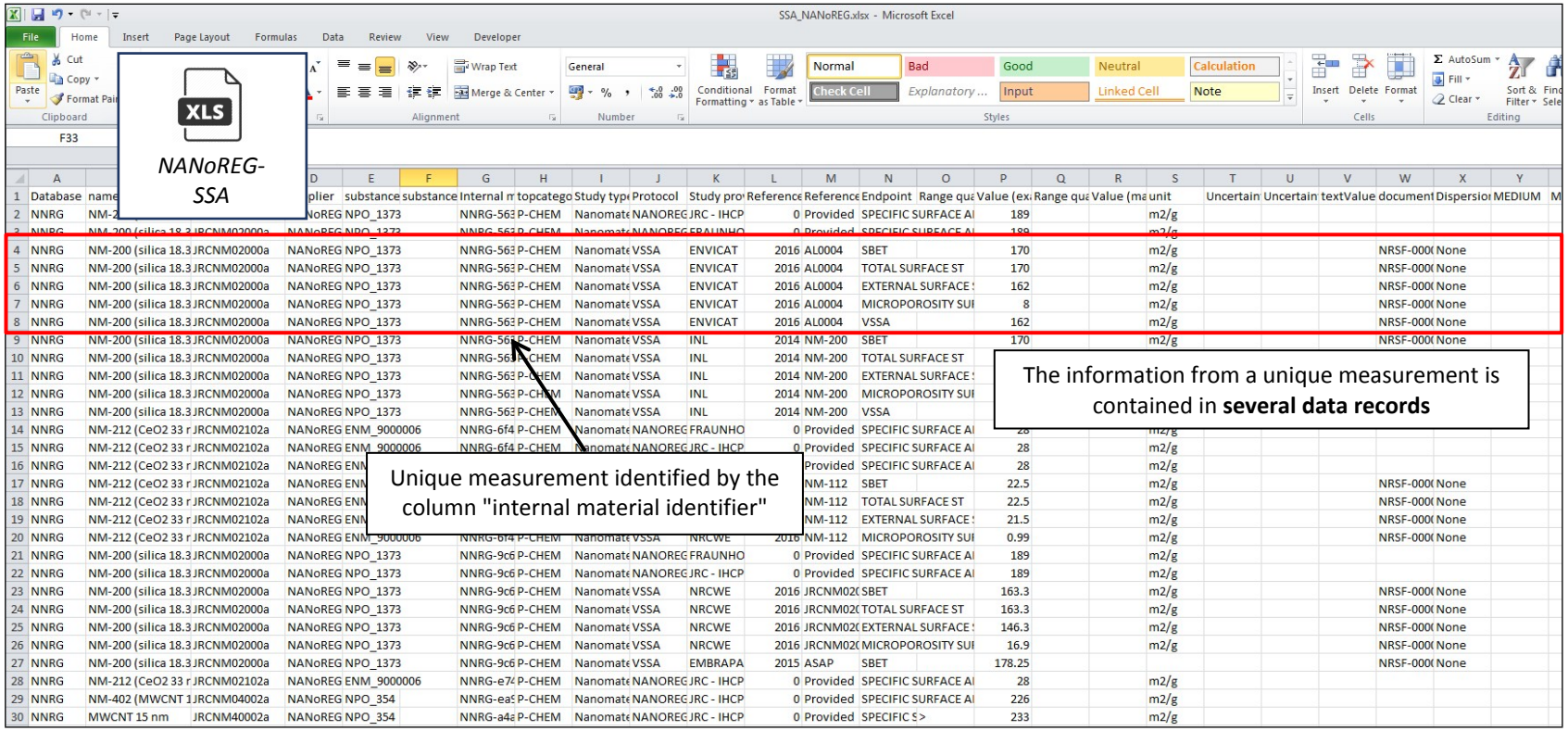
(i) Data extraction

Database queried (Project>Physchem) and extracted → Extracted data manually screened for Group 1 NMs (Table 1) → Extracted data manually screened for selected characterisation techniques (Figure 1)

OUTPUT: A series of spreadsheets with extracted data

- Each file contains all the relevant data records for a given property and project, filtered by NM and techniques selected by GRACIOUS
- Each data record includes (meta)data associated to a unique experiment performed using a specific characterisation technique

NANoREG-Size *NANoREG-SSA* *NANoREG-Shape*



(ii) Data Cleaning

Extracted data searched for information items requested by templates → Data Cleaning step 1: Correction of entry errors → Data Cleaning step 2: Data conversion → Data Cleaning step 3: Duplicate elimination

- correction of typos;
- attribution of the right technique or NM name;
- insertion of missing measurement units

Values are corrected to comply with the information items requested by each template (e.g. conversion of units)

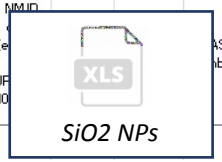
(iii) Data Transfer

Cleaned data transferred from the extraction files to the templates → Data rows in templates not containing property values discarded →

OUTPUT: Series of excel workbooks (GRACIOUS templates)

- each file contains structured relevant data for a given NM or NM group
- Each data row includes all data associated to a unique measurement

SiO_2 NPs *CeO_2 NPs* *$BaSO_4$ NPs* ....



SiO2 NPs

BET analysis template

Sample Information																	Method and instrument information / sample filtration process													Results				SOP
Replicate number	NMID (e... JR... 10...				AS ...ber	Vial number	NM supplier	Material State (liquid or fluid, fluid dispersion, powder)	Use of dispersant: Yes/No (e.g. for Ag NPs NM-300K or	Dispersant reference (indicate here the referen	Sample Name (internal reference)	reporting organisation	operator	date of preparation	date of analysis	instrument type	sample weight (g)	cell type	degassing ramp (Y or N)	outgassing time (min)	outgassing temperature (°C)	backfilling gas	sample weight after degassing (g)	adsorbent gas and temperature (°C)	Analysis points	Isotherme used	SBET (m^2/g)	Total surface St (m^2/g)	External surface Sw (m^2/g)	Microporosity surface S_μ (m^2/g)	VSSA = Sw* density, m^2/cm^3	Associated error	references to SOPs
												LEITAT				Quantachrome Autosorb-1-MP, USA				120	150			-196,15	7	Type IV							
	NM-200	(silica 18.3 nm)				7633	NANoREG				NNBG-9c6d9f81-bd97-bf01-8a	EMBRAPA				Micromeritics ASAP	0.185		Y	8	100	nitrogen			48		178.25							
	NM-200	(silica 18.3 nm)				multiple	NANoREG				NRSF-00000000-0000-0000-00	ENVICAT		2016			0.5					nitrogen					170	170	162	8			
	NM-200	(silica 18.3 nm)				JRCNM020(	NANoREG				NRSF-00000000-0000-0000-0(	NRCWE		2016		Micromeritics TriS	0.226		Y	6	30	nitrogen											
	NM-200	(silica 18.3 nm)				NM-200	NANoREG				NRSF-00000000-0000-0000-00	INL		2014		ıanta chrome Autosorb	0.0869		Y	3.2													
	NM-200	(silica 18.3 nm)					NANoREG					FRAUNHOFER																					
	NM-200	(silica 18.3 nm)					NANoREG					FRAUNHOFER															189						
	NM-200	(silica 18.3 nm)					NANoREG					JRC - IHCP															189						
	NM-200	(silica 18.3 nm)					NANoREG					JRC - IHCP															189						

All the information from a unique measurement is now included **in one data row**

S5. Completeness scores for template sections, data sources and Group 2 NMs

Figure S5a. Completeness scores for each template section and data source

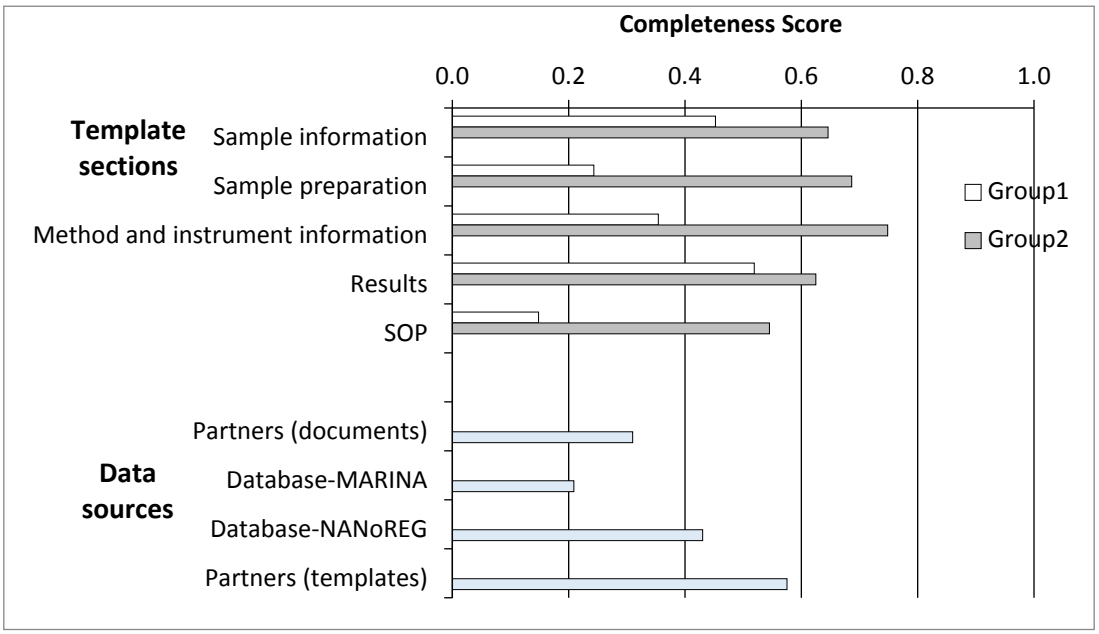


Table S5b. Completeness score (CS) for each Group 2 NM and technique. Green cells: available data. Orange cells: data gaps. White cells represent techniques that are not foreseen to be used: DLS is not appropriate for cellulose nanofibres and Sears titration is only applicable to silica-based materials.

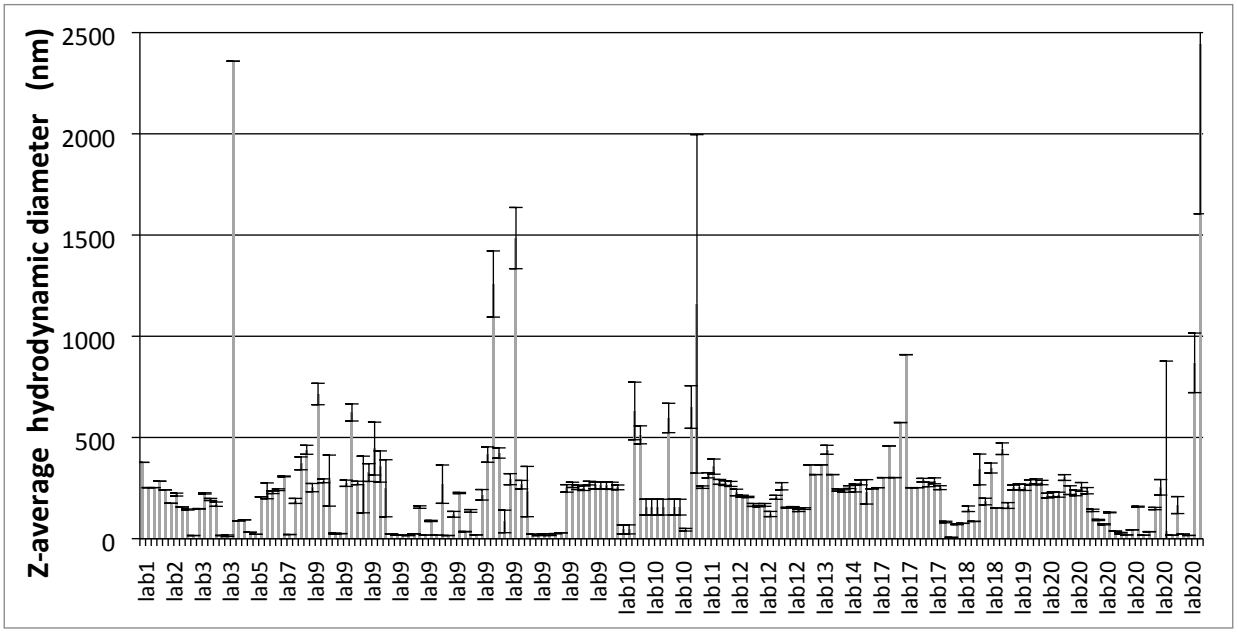
		Silica_unmodified	Silica_Al	Silica_Silane	DPP nano	DPP	DPP coated	CuPhthalo_blue	CuPhthalo_green	Fe2O3_nano_A	Fe2O3_nano_B	CNF-50	CNF-80	CNC-25	*Average CS*
Composition	ICP-MS	0.86	0.86	0.86								0.35	0.36	0.29	0.6
	ICP-OES	0.95	0.95	0.95											0.95
	XRF	0.7	0.7	0.7											0.70
Crystallinity	XRD							0.28		0.28					0.28
Particle shape	TEM											0.25	0.19	0.19	0.21
Particle Size	DLS	0.79	0.79	0.79											0.79
	ES-DMA	0.91	0.91	0.91											0.91
	TEM				0.65	0.65		0.67		0.61		0.3	0.23	0.23	0.48
SSA	BET				0.52	0.64	0.64	0.64	0.64	0.64	0.52				0.60
	Sears titr.	0.89		0.89											0.89
Surface chemistry	ATR-FTIR											0.25	0.21	0.21	0.23
	XPS				0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.28			0.67
Density	Pycnometry											0.46	0.43	0.43	0.44
Dustiness	Small Drum							0.74	0.74	0.72	0.74				0.74
Surface Charge	ELS (for IEP)	0.85	0.85	0.85	0.85	0.85	0.85	0.88	0.88	0.88	0.88				0.86
	ELS (for Z-potential)	0.93	0.93	0.93	0.9	0.9	0.9	0.9	0.89	0.9	0.91				0.91
Surface hydrophob.	Water contact angle				0.64	0.64	0.64	0.64	0.64	0.64	0.64				0.64
	Average CS	0.86	0.86	0.86	0.71	0.73	0.75	0.68	0.75	0.67	0.76	0.31	0.28	0.27	**0.68**

S6 Available property values on priority properties (Group 1 NMs)

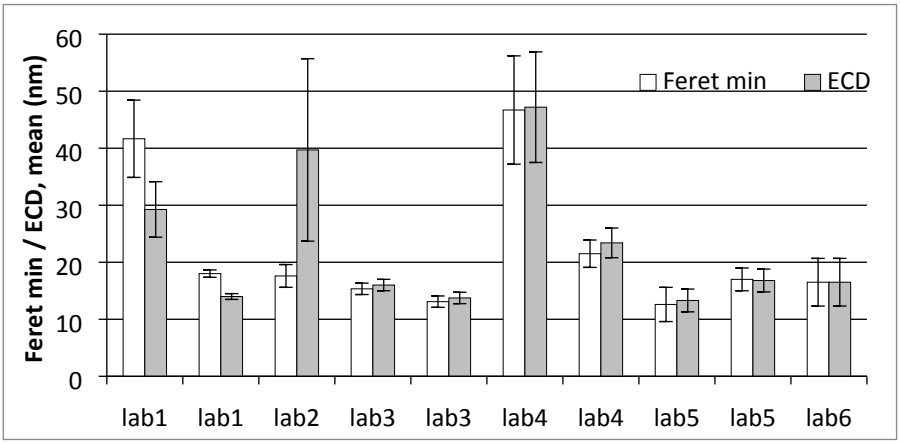
S6.1 Size

Techniques with available data: *DLS*, *TEM* and *CLS.* No available data for: *ES-DMA, sp-ICP-MS*

Available data on *Size* for SiO_2 NPs. Technique: *DLS*



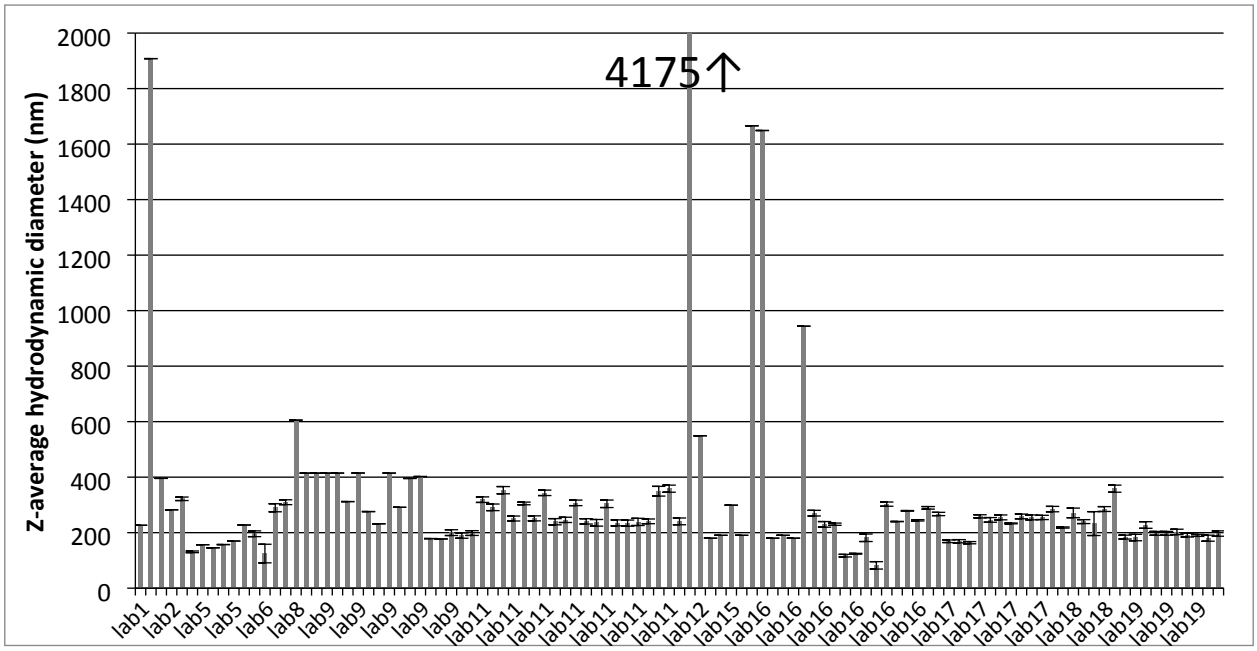
Technique: *TEM*



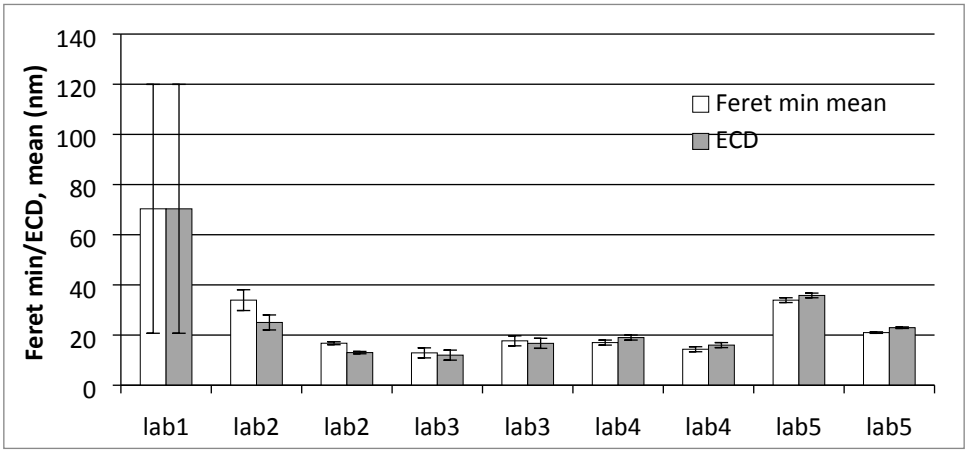
Technique: *CLS*

Organisation	Key information item	Property value	Unit	Uncertainty (SD)
Lab1	Mass weighted mean diameter	563.32	nm	35.78

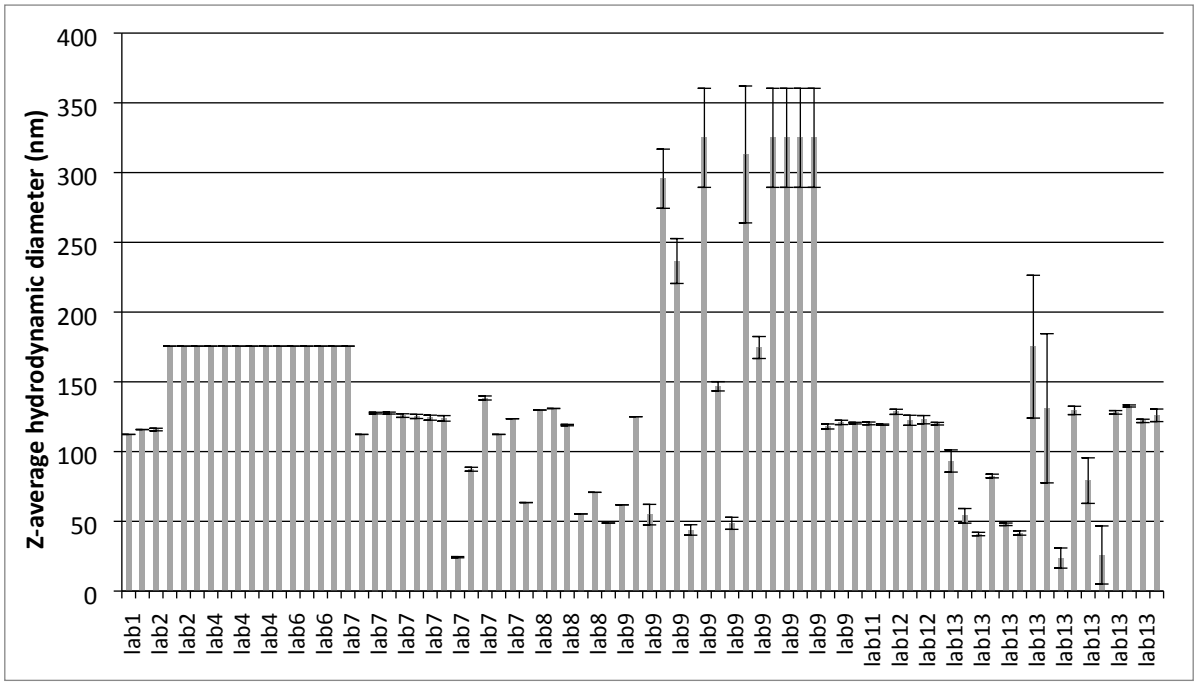
Available data on Size for CeO_2 NPs. Technique: *DLS*



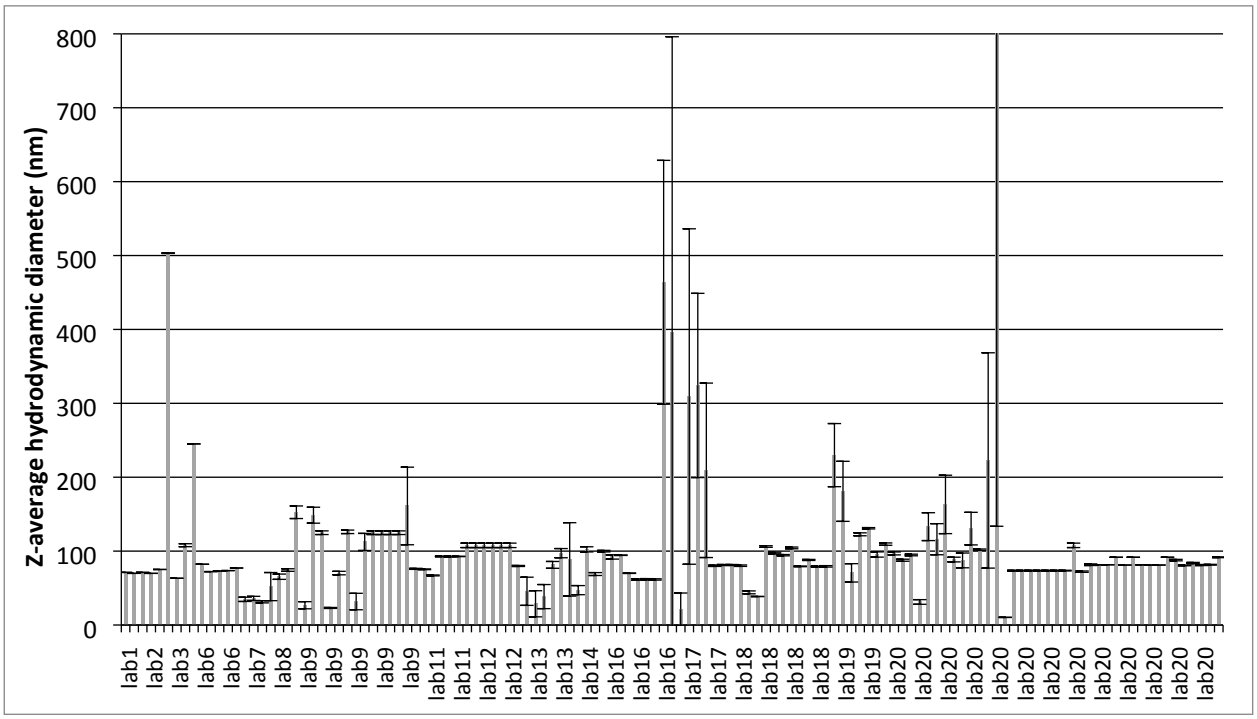
Technique: *TEM*



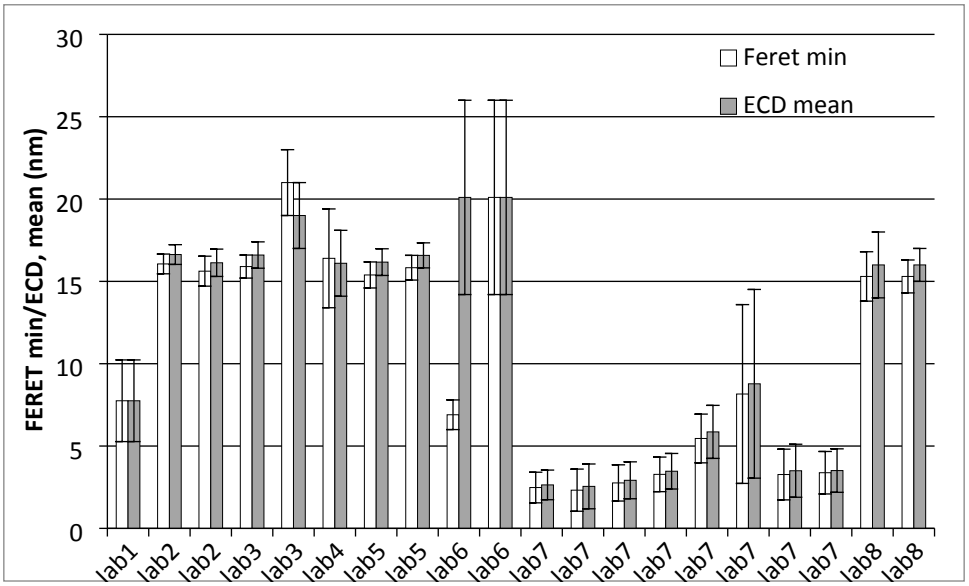
Available data on Size for $BaSO_4$ NPs.Technique: *DLS*



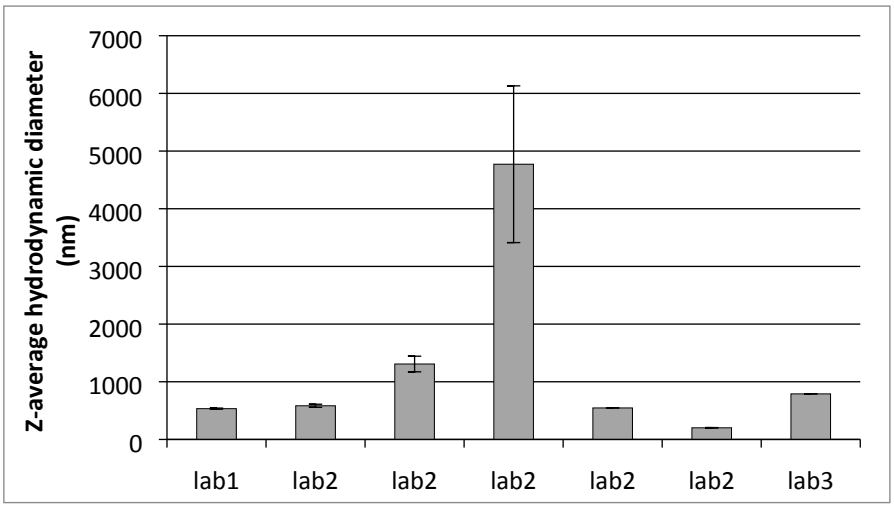
Available data on Size for Ag NPs. Technique: *DLS*



Technique: *TEM*

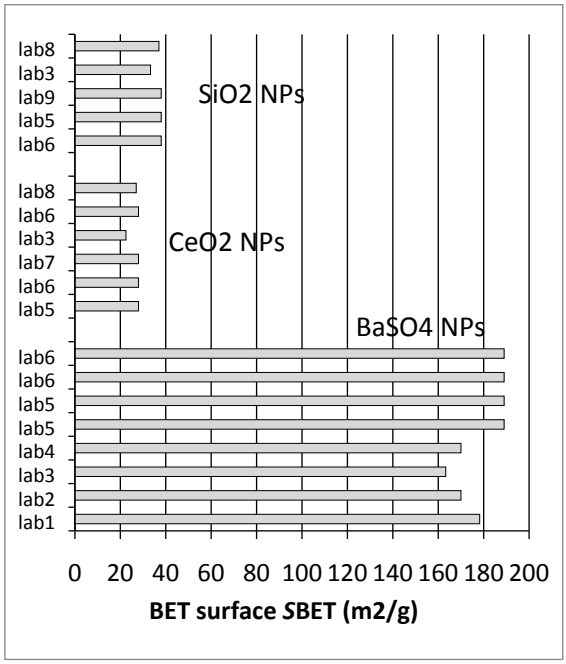


<u>Available data on Size for MWCNTs.</u> Technique: *DLS*



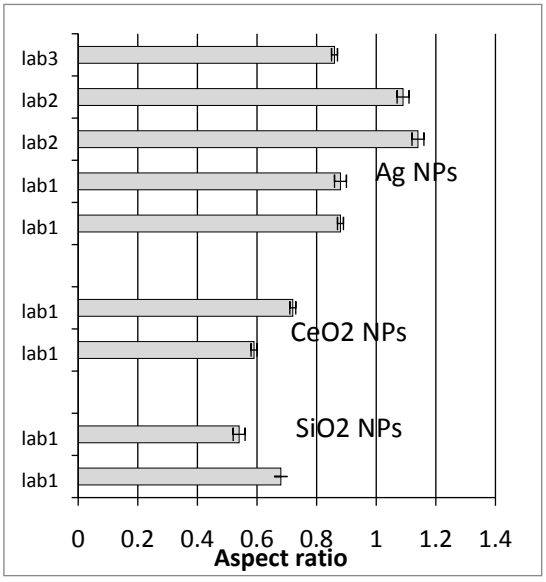
S6.2 Specific surface area

Techniques with available data: *BET analysis*. No available data for: *Sears titration*



S6.3 Particle shape

Technique with available data: *TEM*.



S6.4 Core composition and crystalline phase

Techniques with available data: *EDX, ICP-MS, ICP-OES, XRD, XRF*. No available data for: *WDXRF*.

Material	Technique	Key information item	Organi-sation	Value	Unit	Uncertainty (SD)
CeO_2 NPs	EDX	Elemental composition Ce	lab1	33.00	%	5
CeO_2 NPs	EDX	Elemental composition O	lab1	66.00	%	5
CeO_2 NPs	ICP-OES	Elemental composition Al	lab2	100	mg/kg	n.r.
CeO_2 NPs	ICP-OES	Elemental composition K	lab2	200	mg/kg	n.r.
CeO_2 NPs	ICP-OES	Elemental composition Mg	lab2	200	mg/kg	n.r.
CeO_2 NPs	ICP-OES	Elemental composition Na	lab2	1100	mg/kg	n.r.
CeO_2 NPs	ICP-OES	Elemental composition Zn	lab2	100	mg/kg	n.r.
CeO_2 NPs	XRF	Purity of substance	lab3	> 99.5%	%	n.r.
CeO_2 NPs	XRD	Crystalline phases and %	lab3	cerianite, cubic	n.r.	n.r.
$BaSO_4$ NPs	CHN-ANALYSIS	Total C weight content	lab2	0.96	%	n.r.
$BaSO_4$ NPs	CHN-ANALYSIS	Total H weight content	lab2	0.18	%	n.r.
$BaSO_4$ NPs	CHN-ANALYSIS	Total N weight content	lab2	0.7	%	n.r.
$BaSO_4$ NPs	ICP-OES	Elemental composition Ba	lab2	572400	mg/kg	n.r.
$BaSO_4$ NPs	ICP-OES	Elemental composition Ca	lab2	100	mg/kg	n.r.
$BaSO_4$ NPs	ICP-OES	Elemental composition In	lab2	100	mg/kg	n.r.
$BaSO_4$ NPs	ICP-OES	Elemental composition Mg	lab2	200	mg/kg	n.r.
$BaSO_4$ NPs	ICP-OES	Elemental composition Na	lab2	3600	mg/kg	n.r.
$BaSO_4$ NPs	ICP-OES	Elemental composition Sr	lab2	4100	mg/kg	n.r.
$BaSO_4$ NPs	XRF	Purity of substance	lab3	> 93.8%	%	n.r.
$BaSO_4$ NPs	XRD	Crystalline phases and %	lab3	orthorhomb.	n.r.	n.r.
Ag NPs	CHN-ANALYSIS	Total C weight content	lab2	6.66	%	0.02
Ag NPs	CHN-ANALYSIS	Total C weight content	lab2	6.42	%	0.28
Ag NPs	CHN-ANALYSIS	Total H weight content	lab2	7.98	%	0.05
Ag NPs	CHN-ANALYSIS	Total H weight content	lab2	7.74	%	0.82
Ag NPs	CHN-ANALYSIS	Total N weight content	lab2	3.61	%	0.05
Ag NPs	CHN-ANALYSIS	Total N weight content	lab2	3.43	%	0.09
Ag NPs	ICP-MS	Elemental composition Al	lab4	49363	ppm	n.r.
Ag NPs	ICP-MS	Elemental composition Fe	lab4	3568	ppm	n.r.
Ag NPs	ICP-MS	Elemental composition Co	lab4	2084	ppm	n.r.
Ag NPs	ICP-OES	Elemental composition Na	lab2	100	mg/kg	n.r.
Ag NPs	ICP-OES	Elemental composition Al	lab2	200	mg/kg	n.r.
Ag NPs	ICP-OES	Elemental composition Ca	lab2	200	mg/kg	n.r.
Ag NPs	ICP-OES	Elemental composition Na	lab2	500	mg/kg	n.r.
Ag NPs	ICP-OES	Elemental composition Ag	lab5	9646.7	ppb	n.r.
Ag NPs	ICP-OES	Elemental composition Ag	lab5	2960.3	ppb	n.r.
Ag NPs	ICP-OES	Elemental composition Ag	lab5	3142.3	ppb	n.r.
Ag NPs	ICP-OES	Elemental composition Ag	lab5	7765.1	ppb	n.r.
Ag NPs	ICP-OES	Elemental composition Ag	lab5	1554	ppb	n.r.

Ag NPs	ICP-OES	Elemental composition Ag	lab5	2448.6	ppb	n.r.
MWCNTs	ICP-MS	Elemental composition Al	lab4	3076	ppm	n.r.
MWCNTs	ICP-MS	Elemental composition Al	lab4	7135	ppm	7135
MWCNTs	ICP-MS	Elemental composition Fe	lab4	2376	ppm	n.r.
MWCNTs	ICP-MS	Elemental composition Fe	lab4	17136	ppm	1111
MWCNTs	ICP-MS	Elemental composition Co	lab4	2.3	ppm	n.r.
MWCNTs	ICP-MS	Elemental composition Co	lab4	17.6	ppm	0.8
MWCNTs	ICP-MS	Elemental composition Na	lab4	580	ppm	n.r.
MWCNTs	ICP-OES	Elemental composition Al	lab5	270.9	ppb	n.r.
MWCNTs	ICP-OES	Elemental composition Co	lab5	126	ppb	n.r.
MWCNTs	ICP-OES	Elemental composition Co	lab5	168	ppb	n.r.
MWCNTs	ICP-OES	Elemental composition Al	lab5	103.2321	ppb	n.r.
MWCNTs	ICP-OES	Elemental composition Al	lab5	37.43205	ppb	n.r.

n.r. = not reported

S6.5 Surface chemistry

Techniques with available data: *ATR-FTIR, XPS, TGA*. No available data for *MALDI-TOF, STEM-EDS.*

NM	Organisation	Technique	Measured value	Value	Unit	Uncertainty (SD)
SiO_2 NPs	lab1	TGA	Weight loss	9.02	w/w%	n.r.
SiO_2 NPs	lab2	XPS	Surface composition Si	34.02	%	0.37
SiO_2 NPs	lab2	XPS	Surface composition O	63.61	%	n.r.
SiO_2 NPs	lab2	TGA	Surface composition Ti	0.2	%	0.12
SiO_2 NPs	lab2	XPS	Surface composition Na	0.52	%	0.07
SiO_2 NPs	lab2	XPS	Surface composition S	0.09	%	0.04
SiO_2 NPs	lab2	TGA	Surface composition C	1.57	%	0.34
CeO_2 NPs	lab3	XPS	Surface composition C	79.9	%	n.r.
CeO_2 NPs	lab3	XPS	Surface composition O	17.2	%	n.r.
CeO_2 NPs	lab3	XPS	Surface composition Ce	2.4	%	n.r.
$BaSO_4$ NPs	lab4	TGA	Weight loss	1.9	w/w%	n.r.
$BaSO_4$ NPs	lab3	XPS	Surface composition O	52	%	n.r.
$BaSO_4$ NPs	lab3	XPS	Surface composition Ba	13	%	n.r.
$BaSO_4$ NPs	lab3	XPS	Surface composition C	17	%	n.r.
$BaSO_4$ NPs	lab3	XPS	Surface composition S	11	%	n.r.
$BaSO_4$ NPs	lab3	XPS	Surface composition Cl	3	%	n.r.
$BaSO_4$ NPs	lab3	XPS	Surface composition P	3	%	n.r.
$BaSO_4$ NPs	lab3	XPS	Surface composition N	1	%	n.r.
MWCNTs	lab4	TGA	Weight loss	90	w/w%	n.r.

n.r. = not reported