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Supplementary information

Biosynthesis of inorganic nanomaterials using microbial cells and bacteriophages

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Supplementary Information for:

Biosynthesis of inorganic nanomaterials using microbial cells and bacteriophages

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Supplementary Tables

Table S1 | **Summary of biosynthesized alkali metal- and alkaline earth metal-based NMs using microalgae, bacteria, fungi, and bacteriophages.**

NM	Size (nm)	Shape	Microorganism classification	Species	Ref.
Amorphous Li	950±150	Polygon, Disk	Bacteria	*Pseudomonas aeruginosa* SM1	1
$LiFePO_4/C$	50−400	Hierarchical	Microalgae	Spirulina	2
CdCs	Atypical	Spherical	Genetically engineered bacteria	*Escherichia coli*	3
MgO	<30	Spherical, Oval	Bacteria	*Lactobacillus* sp.	4
MgO	45.12−95.37	Heterogeneous	Fungi	*Trichoderma viride*	5
$CaCO_3$	42.1	Spherical	Bacteria	*Bacillus subtilis*	6
$CaCO_3$	20−30	Hollow spherical	Bacteria	*Proteus mirabilis*	7
$SrCO_3$	20−70	Irregular	Bacteria	*P. mirabilis*	8
$SrCO_3$	10−50	Needle	Fungi	*Fusarium oxysporum*	9
$SrTiO_3$	10−30	Wire	Genetically engineered bacteriophage	M13 bacteriophage	10
SrPr	3.26−3.98	Spherical	Genetically engineered bacteria	*E. coli*	3
SrGd	8.09−9.71	Spherical	Genetically engineered bacteria	*E. coli*	3
Amorphous $BaCO_3$	300	Rod	Bacteria	*P. mirabilis*	7
$BaCO_3$	5.02±0.15	Spherical	Genetically engineered bacteria	*E. coli*	11
$BaTiO_3$	20−80	Spherical	Bacteria	*Lactobacillus* sp.	12
$BaTiO_3$	4−5	Spherical	Fungi	*F. oxysporum*	13
$BaTiO_3$	20−30	Anisotropic	Genetically engineered bacteriophage	M13 bacteriophage	14

The symbol (−) indicates that the data is not available.

Table S2 | **Summary of biosynthesized transition metal-based NMs using microalgae, bacteria, fungi, and bacteriophages.**

NM	Size (nm)	Shape	Microorganism classification	Species	Ref.
Ti/TiO_2	5.81−8.95	Spherical	Bacteria	*Pseudomonas putida*	15
Ti/TiO_2	2−16	Spherical	Fungi	*Trichoderma harzianum*	15
TiO_2	28−54	Spherical, Uneven	Bacteria	*Aeromonas hydrophila*	16
TiO_2	15.23−87.6	Spherical	Bacteria	*Bacillus amyloliquefaciens*	17
TiO_2	16.3±5.5	Spherical	Bacteria	*B. licheniformis*	18
TiO_2	66−77	Spherical, Oval	Bacteria	*B. subtilis*	19
TiO_2	24.63±0.32	Spherical	Bacteria	*Lactobacillus* sp.	20
TiO_2	62−74	Spherical, Oval	Fungi	*Aspergillus flavus*	21
TiO_2	6−13	Spherical	Fungi	*Fusarium oxysporum*	22
TiO_2	12.57±0.22	Spherical	Yeast	*Saccharomyces cerevisiae*	20
C-doped TiO_2/SiO_2	10 (TiO_2)	−	Microalgae	*Cocconeis placentula*	23
Cr	4−50	Spherical	Bacteria	*Bacillus subtilis*	24
Cr_2O_3	8	Spherical	Bacteria	*Bacillus cereus* XMCr-6	25
Mn	13.65±8.60	Spherical	Genetically engineered bacteria	*Escherichia coli*	26
MnO_2	10−70	Spherical	Yeast	*S. cerevisiae*	27
Mn_3O_4	3.93±1.29[a)], 20.84±1.39[b)]	Spherical, Square	Genetically engineered bacteria	*E. coli*	11
γ-MnS	2000-3000	Hexagonal	Bacteria	*Clostridiaceae bacterium* SH021	28
Fe	20.5±5.33	Flake	Bacteria	*Pseudomonas aeruginosa* SM1	1
Fe	8.73	−	Genetically engineered bacteria	*E. coli*	3
Fe	10-24.6	Spherical	Fungi	*Aspergillus oryzae* TFR9	29
$FeCO_3$	10−3000	−	Bacteria	*Geobacter* sp.	30
β-FeOOH	200	Spindle	Bacteria	*Acidithiobacillus ferrooxidans*	31
Fe_2O_3	19	Spherical	Bacteria	*Desulfovibrio desulfuricans aestuarii*	32
Fe_2O_3	9.74±1.19[a)], 10.38±2.04[b)]	Spherical	Genetically engineered bacteria	*E. coli*	11
γ-Fe_2O_3	10	Spherical	Bacteria	*Pseudomonas fluorescens*	33
γ-Fe_2O_3	50	Spherical	Bacteria	*Actinobacter* sp.	34
Fe_3O_4	50−150	Cubic	Bacteria	*Actinobacter* sp.	35
Fe_3O_4	30−50	Hexagonal	Bacteria	*Magnetospirillum magneticum* AMB-1	36
Fe_3O_4	81±23[c)] 58±20[d)]	Rectangular	Bacteria	*Magnetospira* sp.	37
Fe_3O_4	54±12.3[a)] 43±10.9 [b)]	Cuboidal	Bacteria	Magnetotactic bacterium WM-1	38
Fe_3O_4	113±34[a)] 40±5[b)]	Bullet-shaped	Bacteria	Magnetotactic bacteria HSMV-1	39
Fe_3O_4	~30	Spherical	Bacteria	*Magnetospirillum gryphiswaldense* strain MSR-1	40
Fe_3O_4	40–50	Rectangular, rhombic, hexagonal	Bacteria	*Shewanella oneidensis*	41

Fe_3O_4	30–43	Pseudohexagonal, Rhombohedral, Irregular	Bacteria	*S. oneidensis* MR-1	42
Fe_3O_4	4.46±0.27[a)], 6.32±1.47[b)]	Spherical	Genetically engineered bacteria	*E. coli*	11
Fe_3O_4	20	Cubo-octahedral	Genetically engineered bacteria	Magnetospirillum magneticum AMB-1	43
Fe_3O_4	20–50	Quasi-spherical	Fungi	*F. oxysporum*	44
Fe_3O_4	8–14	Wormhole-like	Yeast	Yeast cells	45
FeS	19	Spherical	Bacteria	*Actinobacter* sp.	34
FeS	40−60	Rod	Bacteria	*Geobacter* sp.	30
FeS	30	Spherical	Bacteria	*S. oneidensis* MR-1	46
FeS	2	Spherical	Bacteria	Sulfate-reducing bacteria	47
Fe_3S_4	−	−	Bacteria	Thermophilic magnetotactic bacteria	48
FeAg	−	Spherical	Genetically engineered bacteria	*E. coli*	3
Fe-Mn oxide	370−400	−	Bacteria	*Pseudomonas* sp. QJX-1	49
FeMn	4.47	Spherical	Genetically engineered bacteria	*E. coli*	3
FeCoNi	8.73−13.53	Spherical	Genetically engineered bacteria	*E. coli*	3
FeCoMn	−	−	Genetically engineered bacteria	*E. coli*	3
FePt	10±5	Spherical	Genetically engineered bacteriophage	M13 bacteriophage	50
Co	550±110	Flake	Bacteria	*P. aeruginosa* SM1	1
$Co(CH_3COO)_2$	85	Spherical, Oval	Bacteria	*Bacillus thuringiensis*	51
Co_3O_4	5−7	Spherical	Bacteria	*Brevibacterium casei*	52
Co_3O_4, β-$Co(OH)_2$,	7.06 ± 0.41	Spherical	Genetically engineered bacteria	*E. coli*	11
$CoFe_2O_4$	−	Spherical	Bacteria	*G. sulfurreducens*	53
$CoFe_2O_4$	3-15	Spherical	Yeast	*S. cerevisiae*	54
$CoFe_2O_4$	6.83±0.45[a)], 7.69 ± 0.51[b)]	Spherical	Genetically engineered bacteria	*E. coli*	11
$CoFe_2O_4$	10 and 15	Wire	Genetically engineered bacteriophage	M13 bacteriophage	55
CoPt	10±0.5	Wire	Genetically engineered bacteriophage	M13 bacteriophage	50
NiS	~10	Spherical	Bacteria	*D. alaskensis* G20	56
Ni	2.9±1.2	Polygon	Bacteria	*P. aeruginosa* SM1	1
Ni	12.50±6.69	Spherical	Genetically engineered bacteria	*E. coli*	26
β-$Ni(OH)_2$	25.11±2.67[a)], 28.28±4.49[b)]	Rod, Plate	Genetically engineered bacteria	*E. coli*	11
Ni oxide	1.25-3.8	Spherical	Fungi	*Hypocrea lixii*	57
$NiFe_2O_4$	6.23±0.54[a)], 7.45±1.07[b)]	Spherical	Genetically engineered bacteria	*E. coli*	11
Cu	14.8	Spherical	Bacteria	*E. coli*	58
Cu	10−30	Spherical	Bacteria	*Kocuria flava* M-7	59
Cu	4−60	Spherical	Bacteria	*Morganella psychrotolerans*	60

Cu	49	Spherical, Hexagonal	Bacteria	*P. fluorescens*	61
Cu	11.78±6.60	Spherical	Genetically engineered bacteria	*E. coli*	26
Cu, CuO	5−20	Spherical	Fungi	*Stereum hirsutum*	62
CuO	32	Spherical	Microalgae	*Eichhornia crassipes*	63
CuO	5−45	Spherical	Microalgae	*Bifurcaria bifurcate*	64
Cu_2O	18	Spherical	Bacteria	*Lactobacillus* sp.	65
Cu_2O	17.69±3.23[a)], 4.90±0.25[b)]	Spherical	Genetically engineered bacteria	*E. coli*	11
Cu_2O	16	Spherical	Yeast	*S. cerevisiae*	65
CuS	80.8[c)], 17.4[d)]	Rod	Bacteria	*S.oneidensis* MR-1	66
CuS	2−5	Irregular	Fungi	*F. oxysporum*	67
CuS	10−40	Irregular	Fungi	*F. oxysporum*	68
$CuAlO_2$	5	Spherical	Fungi	*Humicola* sp.	69
Cu_2Se	100	Spherical	Bacteria	*Pantoea agglomerans*	70
$Cu_{2-x}Se$	80	Spherical	Bacteria	*P. agglomerans*	71
Amorphous Y	4.10±0.22	Spherical	Genetically engineered bacteria	*E. coli*	11
ZrO_2	7−8	Spherical	Fungi	*F. oxysporum*	72
Amorphous Zr	21.78±2.34[a)], 34.89±3.38[b)]	Irregular	Genetically engineered bacteria	*E. coli*	11
MoO_2	20.58±1.70	Rod	Genetically engineered bacteria	*E. coli*	11
TcO_2	2	Spherical	Bacteria	*Anaeromyxobacter dehalogenans* strain 2CP-C	73

[a)] NM synthesized *in vivo*; [b)] NM synthesized *in vitro*; [c)] width; [d)] length.
The symbol (−) indicates that the data are not available.

Table S3 | **Summary of biosynthesized noble metal-based NMs using microalgae, bacteria, fungi, and bacteriophages.**

NM	Size (nm)	Shape	Microorganism classification	Species	Ref.
Ru	8.3±5.4	Spherical, Disk	Bacteria	*Pseudomonas aeruginosa* SM1	1
Rh	2.1±0.9	Polygon	Bacteria	*P. aeruginosa* SM1	1
Rh	3.0−4.5	Spherical	Bacteriophage	T4 bacteriophage	74
Pd	15−40	Spherical	Bacteria	*Bacillus sp.* GP	75
Pd	340.46	Spherical	Bacteria	*Shewanella oneidensis* MR-1	76
Pd	22.1±6.2	Polygon, Disk	Bacteria	*P. aeruginosa* SM1	1
Pd	3-30	Irregular	Bacteria	*Paracoccus denitrificans*	77
Pd	3-30	Irregular	Bacteria	*Pseudomonas putida*	77
Pd	3.0−4.5	Spherical	Bacteriophage	T4 bacteriophage	74
Pd	14.3	Spherical	Genetically engineered bacteria	*Escherichia coli*	58
Pd	14.82±4.74	Spherical	Genetically engineered bacteria	*E. coli*	26
Pd	10−50	Spherical	Genetically engineered bacteria	*S. oneidensis*	78
Pd	16.9±4.0−27.9±5.0	Wire	Genetically engineered bacteriophage	E3-M13 bacteriophage	79
PdPt	59.9	Flower	Bacteria	*S. oneidensis* MR-1	76
PdPt	3−40	Spherical	Bacteria	*S. oneidensis* MR-1	80
Pd/Fe_3O_4	5.5±2.2	Spherical, Rod	Bacteria	*S. oneidensis* MR-1	81
PdAu/Fe_3O_4	10-18[a)], 140-190[b)]	Rod	Bacteria	*S. oneidensis* MR-1	81
Ag	44±9[c)], 8.4±12[d)]	Spherical[a)], Oval[b)]	Actinomycetes	*Streptomyces* sp. NH21	82
Ag	5±3.9	Spherical	Actinomycetes	*Streptomyces* sp. LK3	83
Ag	2-20	Spherical	Microalgae	*Acutodesmus dimorphus*	84
Ag	5-30	Spherical	Microalgae	*Chlorella pyrenoidosa*	85
Ag	9–11	Heterogeneous	Bacteria	*Bacillus licheniformis*	86
Ag	−	Heterogeneous	Bacteria	*Bacillus persicus*	86
Ag	−	Heterogeneous	Bacteria	*Bacillus pumilus*	86
Ag	20-50	Spherical	Bacteria	*E. coli*	87
Ag	6.3±4.9	Spherical, Disk	Bacteria	*P. aeruginosa* SM1	1
Ag	>200	Triangle, Hexagon	Bacteria	*Pseudomonas stutzeri* AG259	88
Ag	19.89±6.53	Spherical	Genetically engineered bacteria	*E. coli*	26
Ag	9.86±1.96[c)], 11.87±2.46[d)]	Spherical	Genetically engineered bacteria	*E. coli*	11
Ag	16.7	Spherical	Genetically engineered bacteria	*E. coli*	58
Ag	5-70	Spherical	Genetically engineered bacteria	Ag-resistant *E. coli*	89
Ag	2.0-13.8	Spherical	Fungi	*Aspergillus terrerus*	90
Ag	50−200	Spherical	Fungi	*Phaenerochaete chrysosporium*	91
Ag	20−80	Spherical	Yeast	*Candida utilis* NCIM 3469	92

Ag	15	Spherical	Yeast	*Yarrowia lipolytica* NCYC 789	93
Ag_2O	2−20	Spherical	Bacteria	*Lactobacillus mindensis*	94
Ag_2O	4−22	Spherical	Bacteria	*Xanthomonas* sp. P5	95
Ag_2O	−	−	Fungi	*Aspergillus terreus* VIT 2013	96
Ag_2TeO_3	18.90±1.02 [c)], 21.21±0.81 [d)]	Spherical	Genetically engineered bacteria	*E. coli*	11
Ag_2WO_4	12.67±4.28 [c)], 7.56±1.02 [d)]	Spherical	Genetically engineered bacteria	*E. coli*	11
Ag_2S	>200	Triangle, Hexagon	Bacteria	*P. stutzeri* AG259	88
Ag_2S	2–16	Spherical	Bacteria	*S. oneidensis* MR-1	97
Ag_2S	7.8±1.5	Spherical	Bacteria	*S. oneidensis* MR-1	98
Ag_2S	9±3.5	Spherical	Bacteria	*S. oneidensis* MR-1	99
Ag_2S	10.93±1.94 [c)], 13.47±1.21 [d)]	Spherical	Genetically engineered bacteria	*E. coli*	11
IrO_2	−	Wire	Genetically engineered bacteriophage	M13 bacteriophage	100
IrO_2/Au	5 (Au)	Wire	Genetically engineered bacteriophage	M13 bacteriophage	100
Pt	5	Irregular	Bacteria	*Shewanella Microalgae*	
Pt	265.945	Snowflake	Bacteria	*S. oneidensis* MR-1	76
Amorphous Pt	−	Heterogeneous	Bacteria	Sulfate-reducing bacteria	101
Pt	100−1000	Heterogeneous	Bacteria	Sulfate-reducing bacteria	102
Pt	450	Spherical	Bacteria	*P. aeruginosa* SM1	1
Pt	14.5	Spherical	Genetically engineered bacteria	*Escherichia coli*	58
Pt	14.82 ± 4.74	Spherical	Genetically engineered bacteria	*E. coli*	26
Pt	10-100	Hexagonal, Pentagonal, Spherical, Square	Fungi	*F. oxysporum*	103
Pt	4-35	Spherical	Fungi	*Neurospora crassa*	104
Pt	3.0−4.5	Spherical	Bacteriophage	T4 bacteriophage	74
Au	8.25±0.64	Spherical	Bacteria	*Streptomyces clavuligerus*	105
Au	8-12	Spherical	Bacteria	*Sargassum wightii*	106
Au	10	Spherical	Microalgae	*Euglena gracilis*	107
Au	2-100	Spherical	Microalgae	*Galaxaura elongate*	108
Au	8-12	Spherical	Microalgae	*S. wightii*	106
Au	5-30	Spherical	Bacteria	*Bacillus sp.* GP	75
Au	−	Heterogeneous	Bacteria	*B. persicus*	86
Au	−	Heterogeneous	Bacteria	*B. pumilus*	86
Au	20-50	Spherical	Bacteria	*E. coli*	87
Au	5–25	Spherical	Bacteria	*Pseudomonas veronii* AS41G	109
Au	50–60	Rod	Bacteria	*Rhodopseudomonas capsulata*	110
Au	20	Spherical	Bacteria	*Vibrio fischeri*	111

Au	5–20	Spherical	Genetically engineered bacteria	*E. coli*	112
Au	18.2	Spherical	Genetically engineered bacteria	*E. coli*	58
Au	13.37±4.10	Spherical	Genetically engineered bacteria	*E. coli*	26
Au	20.06±2.27	Spherical	Genetically engineered bacteria	*E. coli*	11
Au	690±350	Horn	Genetically engineered bacteria	*E coli*	113
Au	30	Spherical	Genetically engineered bacteria	*Pseudomonas syringae*	111
Au	40	Spherical	Genetically engineered bacteria	*Pseudomonas savastanoi* P48	111
Au	15	Spherical	Genetically engineered bacteria	*Ralostonia solanacerum*	111
Au	20±2.0	Spherical	Fungi	*Rhizopus oryzae*	114
Au	43-63	Spherical	Fungi	*Aspergillus niger*	
Au	20	Spherical	Fungi	*A. niger*	
Au	8.7±6	Spherical	Fungi	*A. niger*	
Au	6-37	Spherical	Fungi	*Aspergillus oryzae*	
Au	3.5±3	Spherical	Fungi	*Aspergillus tamarii*	
Au	5	Spherical	Fungi	*F. oxysporum*	
Au	7.7±4.3	Spherical	Fungi	*Penicillium ochrochloron*	
Au	75	Heterogeneous	Fungi	*Penicillium* sp.	
Au	−	Spherical, Plate	Yeast	*Yarrowia lipolytica* NCIM 3589	115
Au	5-25	Spherical	Genetically engineered bacteriophage	T7 phage	116
Au/Fe_3O_4	10-18[a)], 140-190[b)]	Spherical, Rod	Bacteria	*S. oneidensis* MR-1	81
Au/Ag	5-25	Spherical	Bacteria	*Lyngbya majuscula*	117
Au/Pd/Ag	−	Wire	Yeast	*Pichia pastoris* GS115	118
Au(CdSeZn)	1.25	Atypical pod-like	Genetically engineered bacteria	*E. coli*	3

[a)] width; [b)] length; [c)] NM synthesized *in vivo*; [d)] NM synthesized *in vitro*.
The symbol (−) indicates that the data are not available.

Table S4 | **Summary of biosynthesized post-transition metal-based NMs using microalgae, bacteria, fungi, and bacteriophages.**

NM	Size (nm)	Shape	Microorganism classification	Species	Ref.
α-Al_2O_3	20±2.1	Spherical	Microalgae	*Sargassum ilicifolium*	119
ZnO	330	Flower	Microalgae	*Chlamydomonas reinhardtii*	120
ZnO	57.78	Spherical, Oval	Bacteria	*Aeromonas hydrophila*	121
ZnO	7−19	Spherical	Bacteria	*Lactobacillus plantarum* VITES07	122
ZnO	100−120	Spherical	Bacteria	*Rhodococcus pyridinivorans* NT2	123
ZnO	10.51±1.71 [a)], 6.62±0.35 [b)]	Square [a)], Spherical [b)]	Genetically engineered bacteria	*Escherichia coli*	11
ZnO	–	Square	Fungi	*Pichia fermentans* JA2	124
$Zn_2(PO_4)_3$	100	Needle	Microalgae	*Scenedesmus obliquus*	125
ZnS	~2	Spherical	Bacteria	*Thermoanaerobacter sp.* X513	126
ZnS	6.5	Spherical, Irregular	Bacteria	Sulfate reducing bacteria (*Desulfovibrio* sp., *Clostridiaceae* sp., *Proteiniphilum* sp., *Geotoga* sp., *Sphaerochaeta* sp.)	127
α-ZnS, β-ZnS	8±2 (α-ZnS), 4±1 (β-ZnS)	Spherical	Bacteria	*Clostridiaceae* sp.	128
ZnS	42	Spherical	Fungi	*Fusarium oxysporum*	129
ZnS	~20 [c)], 600–650 [d)]	Wire	Genetically engineered bacteriophage	M13 bacteriophage	50
ZnS	3−5	Wire	Genetically engineered bacteriophage	M13 bacteriophage	130
$ZnFe_2O_4$	8.45±0.61 [a)], 8.75±0.53 [b)]	Spherical	Genetically engineered bacteria	*E. coli*	11
SeZn	3.92	Spherical	Genetically engineered bacteria	*E. coli*	11
β-$Cd(OH)_2$	4.16±0.37 [a)], 54.71±7.40 [b)]	Spherical [a)], Rod [b)]	Genetically engineered bacteria	*E. coli*	11
$CdCO_3$	20–30	Irregular	Bacteria	*Proteus mirabilis*	131
CdS	120−175	Spherical	Microalgae	*Scenedesmus*-24	132
CdS	2−5	Spherical	Bacteria	*E. coli*	133
CdS	10	Spherical	Bacteria	*E. coli*	134
CdS	3–15	Spherical	Bacteria	*E. coli*	135
CdS	8.01±0.25	Spherical	Bacteria	*Rhodopseudomonas palustris*	136
CdS	35.8±12.9	Spherical	Genetically engineered bacteria	*E. coli*	137
CdS	2–6	Spherical	Genetically engineered bacteria	*E. coli*	138
CdS	10	–	Genetically engineered bacteria	*E. coli*	139
CdS	–	Spherical	Yeast	*Schizosaccharomyces pombe*	140

CdS	20	Spherical	Genetically engineered bacteriophage	M13 bacteriophage	130
CdS/CdSe	16.7±0.67	Spherical	Bacteria	*E. coli*	141
CdZn	3.02	Spherical	Genetically engineered bacteria	*E. coli*	3
CdSe	3.31	Spherical	Genetically engineered bacteria	*E. coli*	3
CdTe	2−3	Spherical	Bacteria	*E. coli*	142
CdTe	7.01	Spherical	Genetically engineered bacteria	*E. coli*	3
CdTe	4.8	Spherical	Genetically engineered bacteria	*E. coli*	143
CdTe	15−20	Spherical	Fungi	*F. oxysporum*	144
CdTe	2-3.6	Spherical	Yeast	*Saccharomyces cerevisiae*	145
CdCs	–	Atypical	Genetically engineered bacteria	*E. coli*	3
CdSeZn	5.01	Spherical	Genetically engineered bacteria	*E. coli*	3
CdSeZnTe	–	–	Genetically engineered bacteria	*E. coli*	3
$In(OH)_3$	3.82±0.33 [a)], 31.69±2.85 [b)]	Spherical [a)], Square [b)]	Genetically engineered bacteria	*E. coli*	11
SnO_2	15-40	Spherical	Bacteria	*Erwinia herbicola*	146
SnO_2	5.17±0.33 [a)], 7.72±1.41 [b)]	Spherical	Genetically engineered bacteria	*E. coli*	11
Hg	2-5	Spherical	Bacteria	*Enterobacter* sp.	147
Amorphous Hg	5.25±0.28	Spherical	Genetically engineered bacteria	*E. coli*	11
HgS	1−100	Spherical	Bacteria	*Bacillus cereus* MRS-1	148
Hg−Se	4.3±0.79	Spherical	Bacteria	*Shewanella putrefaciens 200*	149
Hg_3TeO_6	14.09±2.74 [a)], 42.71±13.80 [b)]	Spherical	Genetically engineered bacteria	*E. coli*	11
Pb	5-20	Spherical	Fungi	*Aspergillus* sp.	150
Amorphous Pb	7.04±0.39 [a)], 4.94±0.24 [b)]	Spherical	Genetically engineered bacteria	*E. coli*	11
PbS	2−5	Spherical	Yeast	*Rhodosporidium diobovatum*	151
PbS	2−5	Spherical	Yeast	*Torulopsis* sp.	152
$Pb_3(NO)_3(OH)_5$, $Pb_2(NO)_3(OH)_3$	204.57±43.86	Plate	Genetically engineered bacteria	*E. coli*	11
PbSe	20−160	Rod	Fungi	*Aspergillus terreus*	153
$Pb_5(VO_4)_3OH$	9.60±1.46 [a)], 1318.31±171.05 [b)]	Spherical [a)], Rod [b)]	Genetically engineered bacteria	*E. coli*	11
$PbMoO_4$	9.91±0.46 [a)], 13.01±1.28 [b)]	Spherical, Square	Genetically engineered bacteria	*E. coli*	11
$PbWO_4$	18.61±3.59 [a)], 42.38±4.81 [b)]	Spherical	Genetically engineered bacteria	*E. coli*	11
Bi	3	Rod	Bacteriophage	Thiolated-M13 bacteriophage	154
Bi_2O_3	5−8	Spherical	Fungi	*Fusarium oxysporum*	155

Bi_2S_3	100	Rod	Bacteria	*Clostridiaceae bacterium* SH021	156
Bi_2S_3	6−500	Hexagonal	Bacteria	*Clostridium acetobutylicum*	157
Bi_2Se_3	100	Sheet	Bacteria	*Lysinibacillus* sp. ZYM-1	158
Bi_2Se_3	50−100	Spherical	Bacteria	*Pseudomonas stutzeri NT-I, Pseudomonas sp. RB, Stenotrophomonas maltophilia TI-1, Ochrobactrum anthropi TI-2, and O. anthropi TI-3*	159
$BiMnO_3$	50	Spherical	Fungi	*Humicola* sp.	160

[a] NM synthesized *in vivo*; [b] NM synthesized *in vitro*; [c] width; [d] length.
The symbol (−) indicates that the data are not available.

Table S5 | **Summary of biosynthesized metalloid-based NMs using microalgae, bacteria, fungi, and bacteriophages.**

NM	Size (nm)	Shape	Microorganism classification	Species	Ref.
C-doped TiO_2/SiO_2	10 (TiO_2)	−	Microalgae	*Cocconeis placentula*	23
Si/SiO_2	10	Spherical	Bacteria	*Actinobacter* sp.	161
Si/SiO_2	1.52−8.73	Spherical	Bacteria	*Pseudomonas putida*	15
Si/SiO_2	5-9	Spherical	Fungi	*Trichoderma harzianum*	15
SiO_2	5−15	Spherical	Fungi	*Fusarium oxysporum*	22
As	20−30, 500	Spherical, Fiber	Genetically engineered bacteria	Arsenic-resistant *Escherichia coli*	162
Amorphous As−S	50−100	Spherical	Bacteria	*Desulfotomaculum auripigmentum* sp. nov.	163
As−S	20−100	Tube	Bacteria	*Shewanella* sp. strain HN-41	164
As−S	−	Tube	Bacteria	Ten different *Shewanella* strains	165
As_4S_4	−	Wire	Bacteria	*Shewanella* sp.	166
As−S	411 ± 125	Spherical	Genetically engineered bacteria	*Escherichia coli*	167
Au/As-S	−	Tube	Bacteria	*Shewanella* sp.	168
Sb_2O_3	3−12	Spherical	Bacteria	*Lactobacillus* sp.	169
Sb_2O_3	2−10	Spherical	Yeast	*Saccharomyces cerevisiae*	170
Sb_2S_3	10−35	Spherical	Bacteria	*Serratia marcescens*	171
Te	200	Rod	Bacteria	*Bacillus selenitireducens*	172
Te	–	Rod	Bacteria	*Ochrobactrum* sp. MPV1	173
Te	781±189	Rod	Bacteria	*Rhodococcus aetherivorans* BCP1	174
Te	463±147	Rod	Bacteria	*R. aetherivorans* BCP1	175
Te	600−700	Rod	Bacteria	*Rhodobacter capsulatus*	176
Te	10−200	Rod	Bacteria	*Shewanella oneidensis MR-1*	177
Te	100–200	Rod	Bacteria	*Shewanella* sp.	178
Te	240	Rod	Bacteria	*Shewanella* sp.	178
Te	50	Spherical	Bacteria	*Sulfurospirillum barnesii*	172
Te	7.78−28.42	Rod	Genetically engineered bacteria	*E. coli*	3
Te	35.49±9.16	Rod	Genetically engineered bacteria	*E. coli*	11

The symbol (−) indicates that the data are not available.

Table S6 | **Summary of biosynthesis nonmetal-based NMs using bacteria and fungi.**

NM	Size (nm)	Shape	Microorganism classification	Species	Ref.
Se	185–190	Spherical	Bacteria	*Agrobacterium sp.*	179
Amorphous Se	50–400	Spherical	Bacteria	*Bacillus mycoides* SeITE01	180
Crystalline Se	50–400	Spherical	Bacteria	*Bacillus subtilis*	181
Se	80–220	Spherical	Bacteria	*Bacillus* sp. MSh-1	182
Se	140–200	Spherical	Bacteria	*Duganella* sp.	179
Crystalline Se	100	Spherical	Bacteria	*Enterobacter cloacae* SLD1a-1	183
Se	24–122	Spherical	Bacteria	*Escherichia coli* K-12	184
Se	90–320	Spherical	Bacteria	*Klebsiella pneumonia*	185
Se	−	Spherical	Bacteria	*Lactobacillus acidophilus*	186
Se	>250	−	Bacteria	*Lactobacillus plantarum*	187
Se	−	Spherical	Bacteria	*Ochrobactrum* sp. MPV1	173
Se	118±36, 324±89	Spherical, Rod	Bacteria	*Ochrobactrum* sp. MPV1	188
Se	90-140, 513 ± 92	Spherical, Rod	Bacteria	*Ochrobactrum* sp. MPV1	189
Se	178.3±11.5	Spherical	Bacteria	*Proteus mirabilis* YC801	190
Se	140	Spherical	Bacteria	*Pseudomonas aeruginosa*	191
Se	50–500	Spherical	Bacteria	*Pseudomonas alcaliphila*	192
Crystalline Se	555 ± 308	Rod	Bacteria	*Rhodococcus aetherivorans* BCP1	193
Crystalline Se	300	Spherical	Bacteria	*Sulfurospirillum barnesii*	194
Crystalline Se	300	Spherical	Bacteria	*Selenihalanaerobacter shriftii*	194
Se	100	Spherical	Bacteria	*Shewanella oneidensis* MR-1	195
Se	439	Spherical	Bacteria	*Staphylococcus carnosus*	196
Crystalline Se	30–400	Wire	Bacteria	*Stenotrophomonas bentonitica* BII-R7	197
Se	160–250	Spherical	Bacteria	*Stenotrophomonas maltophilia* SeITE02	198
Se	179 ± 56	Spherical	Bacteria	*S. maltophilia* SeITE02	188
Se	28–123	–	Bacteria	*Streptomyces microflavus*	199
Se	220	Spherical	Bacteria	*Synechococcus leopoliensis*	200
Se	150	Spherical	Bacteria	*Thauera selenatis*	201
Crystalline Se	30–150	Spherical	Bacteria	*Zooglea ramigera*	202
Amorphous Se	105.25±16.05	Spherical	Genetically engineered bacteria	*E. coli*	11
Se	47	Spherical	Fungi	*Aspergillus terreus*	203
Se	30–100	–	Fungi	*Saccharomyces cerevisiae*	204
Crystalline Se	70−90	Spherical	Yeast	*Magnusiomyces ingens*	205

Table S7 | **Summary of biosynthesized lanthanide- and actinide-based NMs using bacteria and fungi.**

NM	Size (nm)	Shape	Microorganism classification	Species	Ref.
Amorphous La	14.31±1.14	Spherical	Genetically engineered bacteria	*Escherichia coli*	11
$La(OH)_3$	28.99±1.87[a)], 32.11±1.57[b)]	Rod	Genetically engineered bacteria	*E. coli*	11
C-doped $LaCoO_3$	−	−	Bacteria	*Bacillus licheniformis* R08	206
Cu-doped $LaCoO_3$	−	−	Yeast	*Pichia pastoris* GS115	207
Amorphous Ce	16.18±1.95	Spherical	Genetically engineered bacteria	*E. coli*	11
CeO_2	8.02	Spherical	Bacteria	*Bacillus* [208]*subtilis*	
CeO_2	5−20	Spherical	Fungi	*Aspergillus niger*	209
CeO_2	12−20	Spherical	Fungi	*Humicola* sp.	210
$Ce(OH)_3$, CeO_2	4.09±0.31[a)], 32.95±1.81[b)]	Spherical[a)], Rod[b)]	Genetically engineered bacteria	*E. coli*	11
$CePO_4$	50	Needle	Yeast	*Saccharomyces cerevisiae*	211
Amorphous Pr	14.82±2.03	Spherical	Genetically engineered bacteria	*E. coli*	11
$Pr(OH)_3$	67.44±5.19[a)], 59.25±5.30[b)]	Rod	Genetically engineered bacteria	*E. coli*	11
PrGd	6.51	Atypical	Genetically engineered bacteria	*E. coli*	3
Amorphous Nd	12.75±1.45	Spherical	Genetically engineered bacteria	*E. coli*	11
$Nd(OH)_3$	61.19±4.17[a)], 80.58±2.63[b)]	Square[a)], Rod[b)]	Genetically engineered bacteria	*E. coli*	11
Amorphous Sm	11.16±1.75	Spherical	Genetically engineered bacteria	*E. coli*	11
$Sm(OH)_3$	171.77±15.47[a)], 173.83±4.53[b)]	Rod	Genetically engineered bacteria	*E. coli*	11
$SmPO_4$	20-200	Atypical	Bacteria	*Pseudomonas fluorescens, Bacillus subtilis*	212
$SmPO_4$	20-200	Atypical	Yeast	*S. cerevisiae*	212
Eu	−	Rod	Bacteria	*Clostridium* sp. 2611	213
Amorphous Eu	15.27±1.35	Spherical	Genetically engineered bacteria	*E. coli*	11

$Eu(OH)_3$	6.52±0.93[a], 6.89±0.57[b]	Rod	Genetically engineered bacteria	*E. coli*	11
EuSe	2.58±0.29	Spherical	Genetically engineered bacteria	*E. coli*	214
Amorphous Gd	15.53±1.20	Spherical	Genetically engineered bacteria	*E. coli*	11
$Gd(OH)_3$	5.49±0.50[a], 6.89±0.57[b]	Rod	Genetically engineered bacteria	*E. coli*	11
Amorphous $YbPO_4$	5-200	Atypical	Yeast	*S. cerevisiae*	215
U(IV)	18–200	−	Bacteria	*Desulfovibrio alaskensis* G20	216
U(IV)	−	−	Bacteria	*Geobacter sulfurreducens*	217
U(VI)	50–100[c]	Needle	Bacteria	*Streptomyces sporoverrucosus* dwc-3	218
U(VI)	2–5[d]	Wire	Bacteria	*Shewanella oneidensis* MR-1	219
U(VI)	50–100[c]	Needle	Fungi	*Geotrichum* sp. dwc-1	220
UO_2	5	Spherical	Bacteria	*Anaeromyxobacter dehalogenans*	73
UO_2	1.5−2.5	Spherical	Bacteria	*Desulfosporosinus* sp.	221
UO_2	1–5	Spherical	Bacteria	*S. oneidensis* MR-1	222
UO_2	~2.5	Pseudospherical	Bacteria	*S. oneidensis* MR-1	223
UO_2	0.9–5	Spherical	Bacteria	*Shewanella putrefaciens* CN32	224
UO_2	−	−	Bacteria	*Pseudomonas aeruginosa*	225
$HUO_2PO_4\cdot 4H_2O$	1000-2000	Needle	Yeast	*Saccharomyces cerevisiae*	226
$H_2(UO_2)_2(PO_4)_2\cdot 8H_2O$	−	−	Yeast	*S. cerevisiae*	227
$H_3OUO_2PO_4\cdot 3H_2O$, UO_2, $K(UO_2)PO_4\cdot 3H_2O$	−	−	Bacteria	*Bacillus mucilaginosus*	228
$NH_4(UO_2)PO_4\cdot 3H_2O$	−	Needle	Bacteria	*Bacillus cereus* 12-2	229

[a] NM synthesized *in vivo*; [b] NM synthesized *in vitro*; [c] length; [d] width.

References

1 Srivastava, S. K. & Constanti, M. Room temperature biogenic synthesis of multiple nanoparticles (Ag, Pd, Fe, Rh, Ni, Ru, Pt, Co, and Li) by *Pseudomonas aeruginosa* SM1. *J. Nanopart. Res.* **14**, 831 (2012).

2 Xia, Y. *et al.* Biotemplating of phosphate hierarchical rechargeable $LiFePO_4$/C spirulina microstructures. *J. Mater. Chem.* **21**, 6498-6501 (2011).

3 Park, T. J., Lee, S. Y., Heo, N. S. & Seo, T. S. *In vivo* synthesis of diverse metal nanoparticles by recombinant *Escherichia coli*. *Angew. Chem., Int. Ed.* **49**, 7019-7024 (2010).

4 Mohanasrinivasan, V. *et al.* Biosynthesis of MgO nanoparticles using *Lactobacillus* sp. and its activity against human leukemia cell lines HL-60. *BioNanoScience* (2017).

5 Alrabadi, N. I., Thalij, K. M., Hussein, E. I. & Al-Trad, B. M. Antibacterial activity of Ag and MgO nanoparticles synthesized by *Trichoderma viride J. Appl. Environ. Biol. Sci.* **7**, 94-101 (2017).

6 Yi, H. & Qian, C.-X. Synthesis and characterization of calcium carbonate nanoparticles via bacterial mineralization in steel slag comprising cementitious materials. *Sci. Adv. Mater.* **12**, 760-768 (2020).

7 Chen, L. *et al.* Bacteria-mediated synthesis of metal carbonate minerals with unusual morphologies and structures. *Cryst. Growth Des.* **9**, 743-754 (2009).

8 Kang, S., Kim, Y., Lee, Y. J. & Roh, Y. Microbially induced precipitation of strontianite nanoparticles. *J. Nanosci. Nanotechnol.* **15**, 5362-5365 (2015).

9 Rautaray, D., Sanyal, A., Adyanthaya, S. D., Ahmad, A. & Sastry, M. Biological synthesis of strontium carbonate crystals using the fungus *Fusarium oxysporum*. *Langmuir* **20**, 6827-6833 (2004).

10 Nuraje, N. *et al.* Biotemplated synthesis of perovskite nanomaterials for solar energy conversion. *Adv. Mater.* **24**, 2885-2889 (2012).

11 Choi, Y., Park, T. J., Lee, D. C. & Lee, S. Y. Recombinant *Escherichia coli* as a biofactory for various single- and multi-element nanomaterials. *Proc. Natl. Acad. Sci. USA* **115**, 5944-5949 (2018).

12 Jha, A. K. & Prasad, K. Ferroelectric $BaTiO_3$ nanoparticles: Biosynthesis and characterization. *Colloids Surf., B* **75**, 330-334 (2010).

13 Bansal, V., Poddar, P., Ahmad, A. & Sastry, M. Room-temperature biosynthesis of ferroelectric barium titanate nanoparticles. *J. Am. Chem. Soc.* **128**, 11958-11963 (2006).

14 Jeong, C. K. *et al.* Virus-directed design of a flexible $BaTiO_3$ nanogenerator. *ACS Nano* **7**, 11016-11025 (2013).

15 Farhat, M. G., Haggag, W. M., Thabet, M. S. & Mosa, A. A. Efficacy of silicon and titanium nanoparticles biosynthesis by some antagonistic fungi and bacteria for controlling powdery mildew disease of wheat plants *Int. J. Agric. Technol.* **14**, 661-674 (2018).

16 Jayaseelan, C. *et al.* Biological approach to synthesize TiO_2 nanoparticles using *Aeromonas hydrophila* and its antibacterial activity. *Spectrochim. Acta, Part A* **107**, 82-89 (2013).

17 Khan, R. & Fulekar, M. H. Biosynthesis of titanium dioxide nanoparticles using *Bacillus amyloliquefaciens* culture and enhancement of its photocatalytic activity for the degradation of a sulfonated textile dye Reactive Red 31. *J. Colloid Interface Sci.* **475**, 184-191 (2016).

18 Suriyaraj, S. P. & Selvakumar, R. Room temperature biosynthesis of crystalline TiO_2 nanoparticles using *Bacillus licheniformis* and studies on the effect of calcination on phase structure and optical properties. *RSC Adv.* **4**, 39619-39624 (2014).

19 Kirthi, A. V. *et al.* Biosynthesis of titanium dioxide nanoparticles using bacterium *Bacillus subtilis*. *Mater. Lett.* **65**, 2745-2747 (2011).

20 Jha, A. K., Prasad, K. & Kulkarni, A. R. Synthesis of TiO_2 nanoparticles using microorganisms. *Colloids Surf., B* **71**, 226-229 (2009).
21 Rajakumar, G. *et al.* Fungus-mediated biosynthesis and characterization of TiO_2 nanoparticles and their activity against pathogenic bacteria. *Spectrochim. Acta, Part A* **91**, 23-29 (2012).
22 Bansal, V. *et al.* Fungus-mediated biosynthesis of silica and titania particles. *J. Mater. Chem.* **15**, 2583-2589 (2005).
23 He, J. *et al.* Diatom-templated TiO_2 with enhanced photocatalytic activity: biomimetics of photonic crystals. *Appl. Phys. A* **113**, 327-332 (2013).
24 Kanakalakshmi, A., Janaki, V., Shanthi, K. & Kamala-Kannan, S. Biosynthesis of Cr(III) nanoparticles from electroplating wastewater using chromium-resistant *Bacillus subtilis* and its cytotoxicity and antibacterial activity. *Artif. Cells, Nanomed., Biotechnol.* **45**, 1304-1309 (2017).
25 Dong, G. *et al.* Formation of soluble Cr(III) end-products and nanoparticles during Cr(VI) reduction by *Bacillus cereus* strain XMCr-6. *Biochem. Eng. J.* **70**, 166-172 (2013).
26 Tsai, Y.-J. *et al.* Biosynthesis and display of diverse metal nanoparticles by recombinant *Escherichia coli*. *RSC Adv.* **4**, 58717-58719 (2014).
27 Salunke, B. K., Sawant, S. S., Lee, S. I. & Kim, B. S. Comparative study of MnO_2 nanoparticle synthesis by marine bacterium *Saccharophagus degradans* and yeast *Saccharomyces cerevisiae*. *Appl. Microbiol. Biotechnol.* **99**, 5419-5427 (2015).
28 Liu, X. *et al.* Biosynthesis of high-purity γ-MnS nanoparticle by newly isolated *Clostridiaceae* sp. and its properties characterization. *Bioprocess Biosyst. Eng.* **38**, 219-227 (2015).
29 Tarafdar, J. C. & Raliya, R. Rapid, low-cost, and ecofriendly approach for iron nanoparticle synthesis using *Aspergillus oryzae* TFR9. *J. Nanopart.* **2013**, 4 (2013).
30 Kim, Y., Lee, Y. & Roh, Y. Microbial synthesis of iron sulfide (FeS) and iron carbonate ($FeCO_3$) nanoparticles. *J. Nanosci. Nanotechnol.* **15**, 5794-5797 (2015).
31 Xiong, H., Liao, Y., Zhou, L., Xu, Y. & Wang, S. Biosynthesis of nanocrystal akaganéite from $FeCl_2$ solution oxidized by *Acidithiobacillus ferrooxidans* Cells. *Environ. Sci. Technol.* **42**, 4165-4169 (2008).
32 Das, K. R. *et al.* Native hypersaline sulphate reducing bacteria contributes to iron nanoparticle formation in saltpan sediment: a concern for aquaculture. *J. Environ. Manage.* **206**, 556-564 (2018).
33 Magro, M. *et al.* Enlightening mineral iron sensing in *Pseudomonas fluorescens* by surface active maghemite nanoparticles: involvement of the OprF porin. *Biochim. Biophys. Acta, Gen. Subj.* **1860**, 2202-2210 (2016).
34 Bharde, A. A. *et al.* Bacteria-mediated precursor-dependent biosynthesis of superparamagnetic iron oxide and iron sulfide nanoparticles. *Langmuir* **24**, 5787-5794 (2008).
35 Bharde, A. *et al.* Bacterial aerobic synthesis of nanocrystalline magnetite. *J. Am. Chem. Soc.* **127**, 9326-9327 (2005).
36 Chen, C. *et al.* Bacterial magnetic nanoparticles for photothermal therapy of cancer under the guidance of MRI. *Biomaterials* **104**, 352-360 (2016).
37 Zhu, K. *et al.* Isolation and characterization of a marine magnetotactic spirillum axenic culture QH-2 from an intertidal zone of the China Sea. *Res. Microbiol.* **161**, 276-283 (2010).
38 Li, W., Yu, L., Zhou, P. & Zhu, M. A Magnetospirillum strain WM-1 from a freshwater sediment with intracellular magnetosomes. *World J. Microbiol. Biotechnol.* **23**, 1489-1492 (2007).
39 Lefevre, C. T. *et al.* Moderately thermophilic magnetotactic bacteria from hot springs in Nevada. *Appl. Environ. Microbiol.* **76**, 3740-3743 (2010).

40 Guan, F., Li, X., Guo, J., Yang, G. & Li, X. Ganglioside-magnetosome complex formation enhances uptake of gangliosides by cells. *Int. J. Nanomed.* **10**, 6919-6930 (2015).
41 Perez-Gonzalez, T. *et al.* Magnetite biomineralization induced by *Shewanella oneidensis*. *Geochim. Cosmochim. Acta* **74**, 967-979 (2010).
42 Bose, S. *et al.* Bioreduction of hematite nanoparticles by the dissimilatory iron reducing bacterium *Shewanella oneidensis* MR-1. *Geochim. Cosmochim. Acta* **73**, 962-976 (2009).
43 Amemiya, Y., Arakaki, A., Staniland, S. S., Tanaka, T. & Matsunaga, T. Controlled formation of magnetite crystal by partial oxidation of ferrous hydroxide in the presence of recombinant magnetotactic bacterial protein Mms6. *Biomaterials* **28**, 5381-5389 (2007).
44 Bharde, A. *et al.* Extracellular biosynthesis of magnetite using fungi. *Small* **2**, 135-141 (2006).
45 Zhou, W. *et al.* Biosynthesis and magnetic properties of mesoporous Fe_3O_4 composites. *J. Magn. Magn. Mater.* **321**, 1025-1028 (2009).
46 Xiao, X. *et al.* Biosynthesis of FeS nanoparticles from contaminant degradation in one single system. *Biochem. Eng. J.* **105**, 214-219 (2016).
47 Watson, J., Ellwood, D., Soper, A. & Charnock, J. Nanosized strongly-magnetic bacterially-produced iron sulfide materials. *J. Magn. Magn. Mater.* **203**, 69-72 (1999).
48 Lefèvre, C. T., Abreu, F., Lins, U. & Bazylinski, D. A. Nonmagnetotactic multicellular prokaryotes from low-saline, nonmarine aquatic environments and their unusual negative phototactic behavior. *Appl. Environ. Microbiol.* **76**, 3220-3227 (2010).
49 Bai, Y., Yang, T., Liang, J. & Qu, J. The role of biogenic Fe-Mn oxides formed in situ for arsenic oxidation and adsorption in aquatic ecosystems. *Water Res.* **98**, 119-127 (2016).
50 Mao, C. *et al.* Virus-based toolkit for the directed synthesis of magnetic and semiconducting nanowires. *Science* **303**, 213-217 (2004).
51 Marimuthu, S. *et al.* Eco-friendly microbial route to synthesize cobalt nanoparticles using *Bacillus thuringiensis* against malaria and dengue vectors. *Parasitol. Res.* **112**, 4105-4112 (2013).
52 Kumar, U. *et al.* Extracellular bacterial synthesis of protein-functionalized ferromagnetic Co_3O_4 nanocrystals and imaging of self-organization of bacterial cells under stress after exposure to metal ions. *Chem. Mater.* **20**, 1484-1491 (2008).
53 Coker, V. S. *et al.* Harnessing the extracellular bacterial production of nanoscale cobalt ferrite with exploitable magnetic properties. *ACS Nano* **3**, 1922-1928 (2009).
54 Anal K. Jha, K. P. Biological synthesis of cobalt ferrite nanoparticles. *Nanotechnol. Dev.* **2**, 46-51 (2012).
55 Jung, S. M., Qi, J., Oh, D., Belcher, A. & Kong, J. M13 virus aerogels as a scaffold for functional inorganic materials. *Adv. Funct. Mater.* **27**, 1603203 (2017).
56 Capeness, M. J., Edmundson, M. C. & Horsfall, L. E. Nickel and platinum group metal nanoparticle production by *Desulfovibrio alaskensis* G20. *New Biotechnol.* **32**, 727-731 (2015).
57 Salvadori, M. R., Ando, R. A., Nascimento, C. A. & Correa, B. Extra and intracellular synthesis of nickel oxide nanoparticles mediated by dead fungal biomass. *PLoS One* **10**, e0129799 (2015).
58 Ouyang, C.-Y., Lin, Y.-K., Tsai, D.-Y. & Yeh, Y.-C. Secretion of metal-binding proteins by a newly discovered OsmY homolog in *Cupriavidus metallidurans* for the biogenic synthesis of metal nanoparticles. *RSC Adv.* **6**, 16798-16801 (2016).
59 Kaur, H. *et al.* Marine microbe as nano-factories for copper biomineralization. *Biotechnol. Bioprocess Eng.* **20**, 51-57 (2015).
60 Pantidos, N., Edmundson, M. C. & Horsfall, L. Room temperature bioproduction, isolation and anti-microbial properties of stable elemental copper nanoparticles. *New Biotechnol.* **40**, 275-281 (2018).

61 Shantkriti, S. & Rani, P. Biological synthesis of copper nanoparticles using *Pseudomonas fluorescens*. *Int.J.Curr.Microbiol.App.Sci.* **3**, 374-383 (2014).
62 R. Cuevas, N. Durán, M. C. Diez, G. R. Tortella & Rubilar, O. Extracellular biosynthesis of copper and copper oxide nanoparticles by *Stereum hirsutum*, a native white-rot fungus from chilean forests. *J. Nanomater.* **2015**, 7 (2015).
63 Vanathi, P., Rajiv, P. & Sivaraj, R. Synthesis and characterization of *Eichhornia*-mediated copper oxide nanoparticles and assessing their antifungal activity against plant pathogens. *Bull. Mater. Sci.* **39**, 1165-1170 (2016).
64 Abboud, Y. *et al.* Biosynthesis, characterization and antimicrobial activity of copper oxide nanoparticles (CONPs) produced using brown alga extract (*Bifurcaria bifurcata*). *Appl. Nanosci.* **4**, 571-576 (2014).
65 Prasad, K., Jha, A. K., Prasad, K. & Kulkarni, A. R. Can microbes mediate nano-transformation? *Indian J. Phys.* **84**, 1355-1360 (2010).
66 Xiao, X. *et al.* Self-assembly of complex hollow CuS nano/micro shell by an electrochemically active bacterium *Shewanella oneidensis* MR-1. *Int. Biodeterior. Biodegrad.* **116**, 10-16 (2017).
67 Hosseini, M. R., Schaffie, M., Pazouki, M., Darezereshki, E. & Ranjbar, M. Biologically synthesized copper sulfide nanoparticles: Production and characterization. *Mater. Sci. Semicond. Process.* **15**, 222-225 (2012).
68 Schaffie, M. & Hosseini, M. R. Biological process for synthesis of semiconductor copper sulfide nanoparticle from mine wastewaters. *J. Environ. Chem. Eng.* **2**, 386-391 (2014).
69 Ahmad, A. *et al.* Fungus-based synthesis of chemically difficult-to-synthesize multifunctional nanoparticles of $CuAlO_2$. *Adv. Mater.* **19**, 3295-3299 (2007).
70 Yue, L., Wang, J., Qi, S. & Xin, B. Extracellular synthesis of cuprous selenide nanospheres by a biological-chemical coupling reduction process in an anaerobic microbial system. *Biotechnol. Prog.* **32**, 1264-1270 (2016).
71 Qi, S. *et al.* Extracellular biosynthesis of $Cu_{2-x}Se$ nanocrystallites with photocatalytic activity. *Mater. Res. Bull.* **111**, 126-132 (2019).
72 Bansal, V., Rautaray, D., Ahmad, A. & Sastry, M. Biosynthesis of zirconia nanoparticles using the fungus *Fusarium oxysporum*. *J. Mater. Chem.* **14**, 3303-3305 (2004).
73 Marshall, M. J. *et al.* Electron donor-dependent radionuclide reduction and nanoparticle formation by *Anaeromyxobacter dehalogenans* strain 2CP-C. *Environ. Microbiol.* **11**, 534-543 (2009).
74 Hou, L., Gao, F. & Li, N. T4 virus- based toolkit for the direct synthesis and 3D organization of metal quantum particles. *Chem. - Eur. J.* **16**, 14397-14403 (2010).
75 Zhang, H. & Hu, X. Biosynthesis of Pd and Au as nanoparticles by a marine bacterium *Bacillus* sp. GP and their enhanced catalytic performance using metal oxides for 4-nitrophenol reduction. *Enzyme Microb. Technol.* **113**, 59-66 (2018).
76 Tuo, Y. *et al.* Microbial synthesis of bimetallic PdPt nanoparticles for catalytic reduction of 4-nitrophenol. *Environ. Sci. Pollut. Res.* **24**, 5249-5258 (2017).
77 Bunge, M. *et al.* Formation of palladium(0) nanoparticles at microbial surfaces. *Biotechnol. Bioeng.* **107**, 206-215 (2010).
78 Dundas, C. M., Graham, A. J., Romanovicz, D. K. & Keitz, B. K. Extracellular electron transfer by *Shewanella oneidensis* controls palladium nanoparticle phenotype. *ACS Synth. Biol.* **7**, 2726-2736 (2018).
79 Kim, I. *et al.* Virus-templated self-mineralization of ligand-free colloidal palladium nanostructures for high surface activity and stability. *Adv. Funct. Mater.* **27**, 1703262 (2017).
80 Xu, H. *et al.* Microbial synthesis of Pd–Pt alloy nanoparticles using *Shewanella oneidensis* MR-1 with enhanced catalytic activity for nitrophenol and azo dyes reduction. *Nanotechnology* **30**, 065607 (2019).

81 Tuo, Y. *et al.* Microbial synthesis of Pd/Fe_3O_4, Au/Fe_3O_4 and PdAu/Fe_3O_4 nanocomposites for catalytic reduction of nitroaromatic compounds. *Sci. Rep.* **5**, 13515 (2015).

82 Składanowski, M. *et al.* Silver and gold nanoparticles synthesized from *Streptomyces* sp. isolated from acid forest soil with special reference to its antibacterial activity against pathogens. *J. Cluster Sci.* **28**, 59-79 (2017).

83 Karthik, L., Kumar, G., Kirthi, A. V., Rahuman, A. A. & Bhaskara Rao, K. V. Streptomyces sp. LK3 mediated synthesis of silver nanoparticles and its biomedical application. *Bioprocess Biosyst. Eng.* **37**, 261-267 (2014).

84 Chokshi, K. *et al.* Green synthesis, characterization and antioxidant potential of silver nanoparticles biosynthesized from de-oiled biomass of thermotolerant oleaginous microalgae *Acutodesmus dimorphus*. *RSC Advances* **6**, 72269-72274 (2016).

85 Aziz, N. *et al.* Facile algae-derived route to biogenic silver nanoparticles: synthesis, antibacterial, and photocatalytic properties. *Langmuir* **31**, 11605-11612 (2015).

86 Elbeshehy, E. K. F., Elazzazy, A. M. & Aggelis, G. Silver nanoparticles synthesis mediated by new isolates of *Bacillus* spp., nanoparticle characterization and their activity against bean yellow mosaic virus and human pathogens. *Front Microbiol.* **6**, 453 (2015).

87 Kushwaha, A., Singh, V. K., Bhartariya, J., Singh, P. & Yasmeen, K. Isolation and identification of *E. coli* bacteria for the synthesis of silver nanoparticles: characterization of the particles and study of antibacterial activity. *Eur. J. Exp. Biol.* **5**, 65-70 (2015).

88 Klaus, T., Joerger, R., Olsson, E. & Granqvist, C.-G. Silver-based crystalline nanoparticles, microbially fabricated. *Proc. Natl. Acad. Sci. USA* **96**, 13611 (1999).

89 Lin, I. W.-S., Lok, C.-N. & Che, C.-M. Biosynthesis of silver nanoparticles from silver(I) reduction by the periplasmic nitrate reductase c-type cytochrome subunit NapC in a silver-resistant *E. coli*. *Chem. Sci.* **5**, 3144-3150 (2014).

90 Velhal, S. G., Kulkarni, S. D. & Latpate, R. V. Fungal mediated silver nanoparticle synthesis using robust experimental design and its application in cotton fabric. *Int. Nano Lett.* **6**, 257-264 (2016).

91 Vigneshwaran, N., Kathe, A. A., Varadarajan, P. V., Nachane, R. P. & Balasubramanya, R. H. Biomimetics of silver nanoparticles by white rot fungus, *Phaenerochaete chrysosporium*. *Colloids Surf., B* **53**, 55-59 (2006).

92 Waghmare, S. R., Mulla, M. N., Marathe, S. R. & Sonawane, K. D. Ecofriendly production of silver nanoparticles using *Candida utilis* and its mechanistic action against pathogenic microorganisms. *3 Biotech* **5**, 33-38 (2015).

93 Apte, M. *et al.* Psychrotrophic yeast *Yarrowia lipolytica* NCYC 789 mediates the synthesis of antimicrobial silver nanoparticles via cell-associated melanin. *AMB Express* **3**, 32 (2013).

94 Dhoondia, Z. H. & Chakraborty, H. *Lactobacillus* mediated synthesis of silver oxide nanoparticles. *Nanomater. Nanotechnol.* **2**, 15 (2012).

95 Yoo, J.-Y., Jang, E.-Y., Jeong, S.-Y., Hwang, D.-Y. & Son, H.-J. Bacterial indoleacetic acid-induced synthesis of colloidal Ag2O nanocrystals and their biological activities. *Bioprocess Biosyst. Eng.* **42**, 401-414 (2019).

96 Sangappa, M. & Thiagarajan, P. Combating drug resistant pathogenic bacteria isolated from clinical infections, with silver oxide nanoparticles. *Indian. J. Pharm. Sci.* **77**, 151-155 (2015).

97 Debabov, V. *et al.* Bacterial synthesis of silver sulfide nanoparticles. *Nanotechnol. Russ.* **8**, 269-276 (2013).

98 Shebanova, A. S. *et al.* Study of some aspects of the mechanism of bacterial synthesis of silver sulfide nanoparticles by metal-reducing bacteria Shewanella oneidensis MR-1. *Biophysics* **59**, 408-414 (2014).

99 Suresh, A. K. *et al*. Monodispersed biocompatible silver sulfide nanoparticles: facile extracellular biosynthesis using the γ-proteobacterium, *Shewanella oneidensis*. *Acta Biomater.* **7**, 4253-4258 (2011).

100 Nam, Y. S. *et al.* Virus-templated iridium oxide-gold hybrid nanowires for electrochromic application. *Nanoscale* **4**, 3405-3409 (2012).

101 Riddin, T. L., Govender, Y., Gericke, M. & Whiteley, C. G. Two different hydrogenase enzymes from sulphate-reducing bacteria are responsible for the bioreductive mechanism of platinum into nanoparticles. *Enzyme Microb. Technol.* **45**, 267-273 (2009).

102 Riddin, T., Gericke, M. & Whiteley, C. G. Biological synthesis of platinum nanoparticles: Effect of initial metal concentration. *Enzyme Microb. Technol.* **46**, 501-505 (2010).

103 Riddin, T. L., Gericke, M. & Whiteley, C. G. Analysis of the inter- and extracellular formation of platinum nanoparticles by *Fusarium oxysporum* f. sp. *lycopersici* using response surface methodology. *Nanotechnology* **17**, 3482 (2006).

104 Castro-Longoria, E., Moreno-Velazquez, S. D., Vilchis-Nestor, A. R., Arenas-Berumen, E. & Avalos-Borja, M. Production of platinum nanoparticles and nanoaggregates using *Neurospora crassa*. *J. Microbiol. Biotechnol.* **22**, 1000-1004 (2012).

105 Ganesh Kumar, C., Poornachandra, Y. & Chandrasekhar, C. Green synthesis of bacterial mediated anti-proliferative gold nanoparticles: inducing mitotic arrest (G2/M phase) and apoptosis (intrinsic pathway). *Nanoscale* **7**, 18738-18750 (2015).

106 Singaravelu, G., Arockiamary, J. S., Kumar, V. G. & Govindaraju, K. A novel extracellular synthesis of monodisperse gold nanoparticles using marine alga, *Sargassum wightii* Greville. *Colloids Surf., B* **57**, 97-101 (2007).

107 Dahoumane, S. A. *et al.* Improvement of kinetics, yield, and colloidal stability of biogenic gold nanoparticles using living cells of *Euglena gracilis* microalga. *J. Nanopart. Res.* **18**, 79 (2016).

108 Neveen, A.-R., Al-Enazi, N. M. & Ibraheem, I. B. M. Green biosynthesis of gold nanoparticles using *Galaxaura elongata* and characterization of their antibacterial activity. *Arabian J. Chem.* **10**, S3029-S3039 (2017).

109 Baker, S. & Satish, S. Biosynthesis of gold nanoparticles by *Pseudomonas veronii* AS41G inhabiting Annona squamosa L. *Spectrochim. Acta, Part A* **150**, 691-695 (2015).

110 He, S., Zhang, Y., Guo, Z. & Gu, N. Biological synthesis of gold nanowires using extract of *Rhodopseudomonas capsulata*. *Biotechnol. Prog.* **24**, 476-480 (2008).

111 Attaran, N., Eshghi, H., Rahimizadeh, M., Mashreghi, M. & Bakavoli, M. Genetically modified luminescent bacteria *Ralostonia solanacerum*, *Pseudomonas syringae*, *Pseudomonas savastanoi*, and wild type bacterium *Vibrio fischeri* in biosynthesis of gold nanoparticles from gold chloride trihydrate. *Artif. Cells, Nanomed., Biotechnol.* **44**, 263-269 (2016).

112 Seo, J. M., Kim, E. B., Hyun, M. S., Kim, B. B. & Park, T. J. Self-assembly of biogenic gold nanoparticles and their use to enhance drug delivery into cells. *Colloids Surf., B* **135**, 27-34 (2015).

113 Jing, X. *et al.* Microorganism-mediated, CTAC-directed synthesis of SERS-sensitive Au nanohorns with three-dimensional nanostructures by *Escherichia coli* cells. *J. Chem. Technol. Biotechnol.* **90**, 678-685 (2015).

114 Das, S. K., Dickinson, C., Lafir, F., Brougham, D. F. & Marsili, E. Synthesis, characterization and catalytic activity of gold nanoparticles biosynthesized with *Rhizopus oryzae* protein extract. *Green Chem.* **14**, 1322-1334 (2012).

115 Pimprikar, P. S., Joshi, S. S., Kumar, A. R., Zinjarde, S. S. & Kulkarni, S. K. Influence of biomass and gold salt concentration on nanoparticle synthesis by the tropical marine yeast *Yarrowia lipolytica* NCIM 3589. *Colloids Surf., B* **74**, 309-316 (2009).

116 Oh, M. H., Yu, J. H., Kim, I. & Nam, Y. S. Genetically programmed clusters of gold nanoparticles for cancer cell-targeted photothermal therapy. *ACS Appl. Mater. Interfaces* **7**, 22578-22586 (2015).

117 Roychoudhury, P., Ghosh, S. & Pal, R. Cyanobacteria mediated green synthesis of gold-silver nanoalloy. *J. Plant Biochem. Biotechnol.* **25**, 73-78 (2016).

118 Chen, X. *et al.* Microorganism-assisted synthesis of Au/Pd/Ag nanowires. *Mater. Lett.* **165**, 29-32 (2016).

119 Koopi, H. & Buazar, F. A novel one-pot biosynthesis of pure alpha aluminum oxide nanoparticles using the macroalgae *Sargassum ilicifolium*: A green marine approach. *Ceram. Int.* **44**, 8940-8945 (2018).

120 Rao, M. D. & Gautam, P. Synthesis and characterization of ZnO nanoflowers using Chlamydomonas reinhardtii: A green approach. *Environ. Prog. Sustainable Energy* **35**, 1020-1026 (2016).

121 Jayaseelan, C. *et al.* Novel microbial route to synthesize ZnO nanoparticles using Aeromonas hydrophila and their activity against pathogenic bacteria and fungi. *Spectrochim. Acta, Part A* **90**, 78-84 (2012).

122 Selvarajan, E. & Mohanasrinivasan, V. Biosynthesis and characterization of ZnO nanoparticles using *Lactobacillus plantarum* VITES07. *Mater. Lett.* **112**, 180-182 (2013).

123 Kundu, D., Hazra, C., Chatterjee, A., Chaudhari, A. & Mishra, S. Extracellular biosynthesis of zinc oxide nanoparticles using *Rhodococcus pyridinivorans* NT2: multifunctional textile finishing, biosafety evaluation and in vitro drug delivery in colon carcinoma. *J. Photochem. Photobiol. B.* **140**, 194-204 (2014).

124 Chauhan, R., Reddy, A. & Abraham, J. Biosynthesis of silver and zinc oxide nanoparticles using *Pichia fermentans* JA2 and their antimicrobial property. *Appl. Nanosci.* **5**, 63-71 (2015).

125 Santomauro, G. *et al.* Biomineralization of zinc-phosphate-based nano needles by living microalgae. *J. Biomater. Nanobiotechnol.* **3**, 362-370 (2012).

126 Moon, J.-W. *et al.* Manufacturing demonstration of microbially mediated zinc sulfide nanoparticles in pilot-plant scale reactors. *Appl. Microbiol. Biotechnol.* **100**, 7921-7931 (2016).

127 Qi, S. *et al.* High-yield extracellular biosynthesis of ZnS quantum dots through a unique molecular mediation mechanism by the peculiar extracellular proteins secreted by a mixed sulfate reducing bacteria. *ACS Appl. Mater. Interfaces* **11**, 10442-10451 (2019).

128 Yue, L., Qi, S., Wang, J., Cai, J. & Xin, B. Controllable biosynthesis and characterization of α-ZnS and β-ZnS quantum dots: Comparing their optical properties. *Mater. Sci. Semicond. Process.* **56**, 115-118 (2016).

129 Mirzadeh, S., Darezereshki, E., Bakhtiari, F., Fazaelipoor, M. H. & Hosseini, M. R. Characterization of zinc sulfide (ZnS) nanoparticles biosynthesized by *Fusarium oxysporum*. *Mater. Sci. Semicond. Process.* **16**, 374-378 (2013).

130 Mao, C. *et al.* Viral assembly of oriented quantum dot nanowires. *Proc. Natl. Acad. Sci. USA* **100**, 6946 (2003).

131 Kang, S., Kim, Y., Lee, Y. & Roh, Y. Microbially mediated-precipitation of cadmium carbonate nanoparticles. *J. Nanosci. Nanotechnol.* **15**, 418-420 (2015).

132 Jena, J. *et al.* Biological sequestration and retention of cadmium as CdS nanoparticles by the microalga Scenedesmus-24. *J. Appl. Phycol.* **27**, 2251-2260 (2015).

133 Sweeney, R. Y. *et al.* Bacterial biosynthesis of cadmium sulfide nanocrystals. *Chem. Biol.* **11**, 1553-1559 (2004).

134 Yan, Z.-Y., Du, Q.-Q., Qian, J., Wan, D.-Y. & Wu, S.-M. Eco-friendly intracellular biosynthesis of CdS quantum dots without changing *Escherichia coli*'s antibiotic resistance. *Enzyme Microb. Technol.* **96**, 96-102 (2017).

135 Marusak, K. E. *et al.* Cadmium sulphide quantum dots with tunable electronic properties by bacterial precipitation. *RSC Advances* **6**, 76158-76166 (2016).
136 Bai, H. J., Zhang, Z. M., Guo, Y. & Yang, G. E. Biosynthesis of cadmium sulfide nanoparticles by photosynthetic bacteria *Rhodopseudomonas palustris*. *Colloids Surf., B* **70**, 142-146 (2009).
137 Zhang, D. *et al.* Enhanced biosynthesis of CdS nanoparticles through *Arabidopsis thaliana* phytochelatin synthase-modified *Escherichia coli* with fluorescence effect in detection of pyrogallol and gallic acid. *Talanta* **195**, 447-455 (2019).
138 Kang, S. H., Bozhilov, K. N., Myung, N. V., Mulchandani, A. & Chen, W. Microbial synthesis of CdS nanocrystals in genetically engineered *E. coli*. *Angew. Chem., Int. Ed.* **47**, 5186-5189 (2008).
139 Mi, C. *et al.* Biosynthesis and characterization of CdS quantum dots in genetically engineered *Escherichia coli*. *J. Biotechnol.* **153**, 125-132 (2011).
140 Dameron, C. T. *et al.* Biosynthesis of cadmium sulphide quantum semiconductor crystallites. *Nature* **338**, 596 (1989).
141 Órdenes-Aenishanslins, N. *et al.* Biological synthesis of CdS/CdSe core/shell nanoparticles and its application in quantum dot sensitized solar cells. *Front Microbiol.* **10**, 1587 (2019).
142 Bao, H. *et al.* Extracellular microbial synthesis of biocompatible CdTe quantum dots. *Acta Biomater.* **6**, 3534-3541 (2010).
143 Monrás, J. P. *et al.* Enhanced glutathione content allows the in vivo synthesis of fluorescent CdTe nanoparticles by *Escherichia coli*. *PLOS ONE* **7**, e48657 (2012).
144 Syed, A. & Ahmad, A. Extracellular biosynthesis of CdTe quantum dots by the fungus *Fusarium oxysporum* and their anti-bacterial activity. *Spectrochim. Acta, Part A* **106**, 41-47 (2013).
145 Bao, H., Hao, N., Yang, Y. & Zhao, D. Biosynthesis of biocompatible cadmium telluride quantum dots using yeast cells. *Nano Res.* **3**, 481-489 (2010).
146 Srivastava, N. & Mukhopadhyay, M. Biosynthesis of SnO_2 nanoparticles using bacterium *Erwinia herbicola* and their photocatalytic activity for degradation of dyes. *Ind. Eng. Chem. Res.* **53**, 13971-13979 (2014).
147 Sinha, A. & Khare, S. K. Mercury bioaccumulation and simultaneous nanoparticle synthesis by *Enterobacter* sp. cells. *Bioresour. Technol.* **102**, 4281-4284 (2011).
148 Sathyavathi, S., Manjula, A., Rajendhran, J. & Gunasekaran, P. Biosynthesis and characterization of mercury sulphide nanoparticles produced by *Bacillus cereus* MRS-1. *Indian J. Exp. Biol.* **51**, 973-978 (2013).
149 Ho, C. T. *et al.* Biologically based method for the synthesis of Hg-Se nanostructures by *Shewanella* spp. *RSC Advances* **5**, 20764-20768 (2015).
150 Pavani, K. V., Kumar, N. S. & Sangameswaran, B. B. Synthesis of lead nanoparticles by *Aspergillus* species. *Pol. J. Microbiol.* **61**, 61-63 (2012).
151 Seshadri, S., Saranya, K. & Kowshik, M. Green synthesis of lead sulfide nanoparticles by the lead resistant marine yeast, *Rhodosporidium diobovatum*. *Biotechnol. Prog.* **27**, 1464-1469 (2011).
152 Kowshik, M., Vogel, W., Urban, J., Kulkarni, S. K. & Paknikar, K. M. Microbial synthesis of semiconductor PbS nanocrystallites. *Adv. Mater.* **14**, 815-818 (2002).
153 Mary Jacob, J., Balakrishnan, R. M. & Kumar, U. B. Biosynthesis of lead selenide quantum rods in marine *Aspergillus terreus*. *Mater. Lett.* **124**, 279-281 (2014).
154 Vera-Robles, L. I., Escobar-Alarcón, L., Picquart, M., Hernández-Pozos, J. L. & Haro-Poniatowski, E. A biological approach for the synthesis of bismuth nanoparticles: using thiolated M13 phage as scaffold. *Langmuir* **32**, 3199-3206 (2016).
155 Uddin, I. *et al.* Structure and microbial synthesis of sub-10 nm Bi_2O_3 nanocrystals. *J. Nanosci. Nanotechnol.* **8**, 3909-3913 (2008).

156 Yue, L., Wu, Y., Liu, X., Xin, B. & Chen, S. Controllable extracellular biosynthesis of bismuth sulfide nanostructure by sulfate-reducing bacteria in water–oil two-phase system. *Biotechnol. Prog.* **30**, 960-966 (2014).

157 Kamaraj, S. K., Venkatachalam, G., Arumugam, P. & Berchmans, S. Bio-assisted synthesis and characterization of nanostructured bismuth (III) sulphide using *Clostridium acetobutylicum*. *Mater. Chem. Phys.* **143**, 1325-1330 (2014).

158 Zhou, H. *et al.* Bacteria-mediated ultrathin Bi_2Se_3 nanosheets fabrication and their application in photothermal cancer therapy. *ACS Sustainable Chem. Eng.* **6**, 4863-4870 (2018).

159 Kuroda, M. *et al.* Biosynthesis of bismuth selenide nanoparticles using chalcogen-metabolizing bacteria. *Appl. Microbiol. Biotechnol.* (2019).

160 Mazumder, B. *et al.* Bio-milling technique for the size reduction of chemically synthesized $BiMnO_3$ nanoplates. *J. Mater. Chem.* **17**, 3910-3914 (2007).

161 Singh, S. *et al.* Bacterial synthesis of silicon/silica nanocomposites. *J. Mater. Chem.* **18**, 2601-2606 (2008).

162 Edmundson, M. C. & Horsfall, L. Construction of a modular arsenic-resistance operon in *E. coli* and the production of arsenic nanoparticles. *Front. Bioeng. Biotechnol.* **3**, 160 (2015).

163 Newman, D. K. *et al.* Dissimilatory arsenate and sulfate reduction in *Desulfotomaculum auripigmentum* sp. nov. *Arch. Microbiol.* **168**, 380-388 (1997).

164 Lee, J.-H. *et al.* Biogenic formation of photoactive arsenic-sulfide nanotubes by *Shewanella* sp. strain HN-41. *Proc. Natl. Acad. Sci. USA* **104**, 20410 (2007).

165 Jiang, S. *et al.* Biogenic formation of As-S nanotubes by diverse *Shewanella* Strains. *Appl. Environ. Microbiol.* **75**, 6896-6899 (2009).

166 Kim, T.-Y. *et al.* Biogenic realgar As_4S_4 molecular clusters formed by a one-pot microbial-driven process as a Li-ion storage material. *Adv. Sustainable Syst.* **1**, 1700056 (2017).

167 Chellamuthu, P. *et al.* Engineering bacteria for biogenic synthesis of chalcogenide nanomaterials. *Microb. Biotechnol.* **12**, 161-172 (2019).

168 Fang, L., Wilfred, C. & Nosang, V. M. Controlled growth of gold nanocrystals on biogenic As–S nanotubes by galvanic displacement. *Nanotechnology* **29**, 055604 (2018).

169 Jha, A. K., Prasad, K. & Prasad, K. Biosynthesis of Sb_2O_3 nanoparticles: A low- cost green approach. *Biotechnol J.* **4**, 1582-1585 (2009).

170 Jha, A. K., Prasad, K. & Prasad, K. A green low-cost biosynthesis of Sb_2O_3 nanoparticles. *Biochem. Eng. J.* **43**, 303-306 (2009).

171 Bahrami, K., Nazari, P., Sepehrizadeh, Z., Zarea, B. & Shahverdi, A. R. Microbial synthesis of antimony sulfide nanoparticles and their characterization. *Ann. Microbiol.* **62**, 1419-1425 (2012).

172 Baesman, S. M. *et al.* Formation of tellurium nanocrystals during anaerobic growth of bacteria that use Te oxyanions as respiratory electron acceptors. *Appl. Environ. Microbiol.* **73**, 2135-2143 (2007).

173 Zonaro, E. *et al.* *Ochrobactrum* sp. MPV1 from a dump of roasted pyrites can be exploited as bacterial catalyst for the biogenesis of selenium and tellurium nanoparticles. *Microb. Cell. Fact.* **16**, 215 (2017).

174 Presentato, A. *et al.* Assembly, growth and conductive properties of tellurium nanorods produced by *Rhodococcus aetherivorans* BCP1. *Sci. Rep.* **8**, 3923 (2018).

175 Presentato, A. *et al.* *Rhodococcus aetherivorans* BCP1 as cell factory for the production of intracellular tellurium nanorods under aerobic conditions. *Microb. Cell. Fact.* **15**, 204 (2016).

176 Borghese, R. *et al.* Extracellular production of tellurium nanoparticles by the photosynthetic bacterium *Rhodobacter capsulatus*. *J. Hazard. Mater.* **309**, 202-209 (2016).

177 Kim, D.-H., Kanaly, R. A. & Hur, H.-G. Biological accumulation of tellurium nanorod structures via reduction of tellurite by *Shewanella oneidensis* MR-1. *Bioresour. Technol.* **125**, 127-131 (2012).
178 Kim, M. G. *et al.* Unusual Li-ion storage through anionic redox processes of bacteria-driven tellurium nanorods. *J. Mater. Chem.* **3**, 16978-16987 (2015).
179 Bajaj, M., Schmidt, S. & Winter, J. Formation of Se (0) nanoparticles by *Duganella* sp. and *Agrobacterium* sp. isolated from Se-laden soil of North-East Punjab, India. *Microb. Cell Fact.* **11**, 64 (2012).
180 Lampis, S. *et al.* Delayed formation of zero-valent selenium nanoparticles by *Bacillus mycoides* SeITE01 as a consequence of selenite reduction under aerobic conditions. *Microb. Cell Fact.* **13**, 35 (2014).
181 Wang, T., Yang, L., Zhang, B. & Liu, J. Extracellular biosynthesis and transformation of selenium nanoparticles and application in H_2O_2 biosensor. *Colloids Surf., B* **80**, 94-102 (2010).
182 Shakibaie, M., Khorramizadeh, M. R., Faramarzi, M. A., Sabzevari, O. & Shahverdi, A. R. Biosynthesis and recovery of selenium nanoparticles and the effects on matrix metalloproteinase- 2 expression. *Biotechnol. Appl. Biochem.* **56**, 7-15 (2010).
183 Losi, M. & Frankenberger, W. Reduction of selenium oxyanions by *Enterobacter cloacae* SLD1a-1: isolation and growth of the bacterium and its expulsion of selenium particles. *Appl. Environ. Microbiol.* **63**, 3079-3084 (1997).
184 Dobias, J., Suvorova, E. I. & Bernier-Latmani, R. Role of proteins in controlling selenium nanoparticle size. *Nanotechnology* **22**, 195605 (2011).
185 Kazempour, Z. B., Yazdi, M. H., Rafii, F. & Shahverdi, A. R. Sub-inhibitory concentration of biogenic selenium nanoparticles lacks post antifungal effect for *Aspergillus niger* and *Candida albicans* and stimulates the growth of *Aspergillus niger*. *Iran. J. Microbiol.* **5**, 81-85 (2013).
186 Domokos-Szabolcsy, E. *et al.* Accumulation of red elemental selenium nanoparticles and their biological effects in *Nicotinia tabacum*. *Plant Growth Regul.* **68**, 525-531 (2012).
187 Yazdi, M. H., Mahdavi, M., Setayesh, N., Esfandyar, M. & Shahverdi, A. R. Selenium nanoparticle-enriched *Lactobacillus brevis* causes more efficient immune responses in vivo and reduces the liver metastasis in metastatic form of mouse breast cancer. *Daru, J. Pharm. Sci.* **21**, 33 (2013).
188 Piacenza, E. *et al.* Physical-chemical properties of biogenic selenium nanostructures produced by *Stenotrophomonas maltophilia* SeITE02 and *Ochrobactrum* sp. MPV1. *Front. Microbiol.* **9**, 3178-3178 (2018).
189 Piacenza, E. *et al.* Influence of bacterial physiology on processing of selenite, biogenesis of nanomaterials and their thermodynamic stability. *Molecules* **24**, 2532 (2019).
190 Wang, Y. *et al.* Selenium nanoparticle synthesized by *Proteus mirabilis* YC801: an efficacious pathway for selenite biotransformation and detoxification. *Int. J. Mol. Sci.* **19**, 3809 (2018).
191 Dwivedi, S., AlKhedhairy, A. A., Ahamed, M. & Musarrat, J. Biomimetic synthesis of selenium nanospheres by bacterial strain JS-11 and its role as a biosensor for nanotoxicity assessment: a novel Se-bioassay. *PLoS One* **8**, e57404 (2013).
192 Zhang, W. *et al.* Biosynthesis and structural characteristics of selenium nanoparticles by *Pseudomonas alcaliphila*. *Colloids Surf., B* **88**, 196-201 (2011).
193 Presentato, A. *et al.* Biosynthesis of selenium-nanoparticles and -nanorods as a product of selenite bioconversion by the aerobic bacterium *Rhodococcus aetherivorans* BCP1. *New Biotechnol.* **41**, 1-8 (2018).
194 Oremland, R. S. *et al.* Structural and spectral features of selenium nanospheres produced by Se-respiring bacteria. *Appl. Environ. Microbiol.* **70**, 52-60 (2004).

195 Li, D.-B. *et al.* Selenite reduction by *Shewanella oneidensis* MR-1 is mediated by fumarate reductase in periplasm. *Sci. Rep.* **4**, 3735 (2014).
196 Estevam, E. C. *et al.* Natural selenium particles from *Staphylococcus carnosus*: Hazards or particles with particular promise? *J. Hazard. Mater.* **324**, 22-30 (2017).
197 Ruiz Fresneda, M. A. *et al.* Green synthesis and biotransformation of amorphous Se nanospheres to trigonal 1D Se nanostructures: impact on Se mobility within the concept of radioactive waste disposal. *Environ. Sci.: Nano* **5**, 2103-2116 (2018).
198 Lampis, S. *et al.* Selenite biotransformation and detoxification by *Stenotrophomonas maltophilia* SeITE02: Novel clues on the route to bacterial biogenesis of selenium nanoparticles. *J. Hazard. Mater.* **324**, 3-14 (2017).
199 Forootanfara, H. *et al.* Biosynthesis and characterization of selenium nanoparticles produced by terrestrial actinomycete *Streptomyces microflavus* strain FSHJ31. *Res. & Rev.: J. Microbiol. Biotechnol.* **3**, 47-53 (2014).
200 Hnain, A., Brooks, J. & Lefebvre, D. D. The synthesis of elemental selenium particles by *Synechococcus leopoliensis*. *Appl. Microbiol. Biotechnol.* **97**, 10511-10519 (2013).
201 Debieux, C. M. *et al.* A bacterial process for selenium nanosphere assembly. *Proc. Natl. Acad. Sci.* **108**, 13480-13485 (2011).
202 Srivastava, N. & Mukhopadhyay, M. Biosynthesis and structural characterization of selenium nanoparticles mediated by *Zooglea ramigera*. *Powder Technol.* **244**, 26-29 (2013).
203 Zare, B., Babaie, S., Setayesh, N. & Shahverdi, A. R. Isolation and characterization of a fungus for extracellular synthesis of small selenium nanoparticles. *Nanomed. J.* **1**, 13-19 (2013).
204 Hariharan, H., Al-Harbi, N., Karuppiah, P. & Rajaram, S. Microbial synthesis of selenium nanocomposite using *Saccharomyces cerevisiae* and its antimicrobial activity against pathogens causing nosocomial infection. *Chalcogenide Lett.* **9**, 509-515 (2012).
205 Lian, S. *et al.* Characterization of biogenic selenium nanoparticles derived from cell-free extracts of a novel yeast *Magnusiomyces ingens*. *3 Biotech* **9**, 221 (2019).
206 Jia, L. *et al.* Visible-light-induced photocatalyst based on C-doped $LaCoO_3$ synthesized by novel microorganism chelate method. *Catal. Commun.* **10**, 1230-1234 (2009).
207 Wang, L., Pang, Q., Song, Q., Pan, X. & Jia, L. Novel microbial synthesis of Cu doped $LaCoO_3$ photocatalyst and its high efficient hydrogen production from formaldehyde solution under visible light irradiation. *Fuel* **140**, 267-274 (2015).
208 K. Pitchumani, M. L. Priya & Annadurai, G. Biosynthesis of nanoceria from *Bacillus subtilis*: characterization and antioxidant potential. *Res. J. Life Sci., Bioinf., Pharm. Chem. Sci.* **5**, 644 (2019).
209 Gopinath, K., Karthika, V., Sundaravadivelan, C., Gowri, S. & Arumugam, A. Mycogenesis of cerium oxide nanoparticles using *Aspergillus niger* culture filtrate and their applications for antibacterial and larvicidal activities. *J. Nanostruct. Chem.* **5**, 295-303 (2015).
210 Khan, S. A. & Ahmad, A. Fungus mediated synthesis of biomedically important cerium oxide nanoparticles. *Materials Research Bulletin* **48**, 4134-4138 (2013).
211 Jiang, M. *et al.* Biological nano-mineralization of Ce phosphate by *Saccharomyces cerevisiae*. *Chem. Geol.* **277**, 61-69 (2010).
212 Jiang, M., Ohnuki, T. & Utsunomiya, S. Biomineralization of middle rare earth element samarium in yeast and bacteria systems. *Geomicrobiol. J.* **35**, 375-384 (2018).
213 Maleke, M. *et al.* Anaerobic reduction of europium by a Clostridium strain as a strategy for rare earth biorecovery. *Scientific Reports* **9**, 14339 (2019).
214 Kim, E. B., Seo, J. M., Kim, G. W., Lee, S. Y. & Park, T. J. *In vivo* synthesis of europium selenide nanoparticles and related cytotoxicity evaluation of human cells. *Enzyme Microb. Technol.* **95**, 201-208 (2016).

215 Jiang, M. *et al.* Post-adsorption process of Yb phosphate nano-particle formation by *Saccharomyces cerevisiae*. *Geochim. Cosmochim. Acta* **93**, 30-46 (2012).
216 Şengör, S. S. *et al.* Impact of different environmental conditions on the aggregation of biogenic U (IV) nanoparticles synthesized by *Desulfovibrio alaskensis* G20. *BioMetals* **29**, 965-980 (2016).
217 Cologgi, D. L., Lampa-Pastirk, S., Speers, A. M., Kelly, S. D. & Reguera, G. Extracellular reduction of uranium via *Geobacter* conductive pili as a protective cellular mechanism. *Proc. Natl. Acad. Sci. USA* 201108616 (2011).
218 Li, X. *et al.* Bioaccumulation characterization of uranium by a novel *Streptomyces sporoverrucosus* dwc-3. *J. Environ. Sci.* **41**, 162-171 (2016).
219 Jiang, S. *et al.* Bacterial formation of extracellular U (VI) nanowires. *Chem. Commun.* **47**, 8076-8078 (2011).
220 Zhao, C. *et al.* Characterization of uranium bioaccumulation on a fungal isolate *Geotrichum* sp. dwc-1 as investigated by FTIR, TEM and XPS. *J. Radioanal. Nucl. Chem.* **310**, 165-175 (2016).
221 Suzuki, Y., Kelly, S. D., Kemner, K. M. & Banfield, J. F. Radionuclide contamination: nanometre-size products of uranium bioreduction. *Nature* **419**, 134 (2002).
222 Marshall, M. J. *et al.* c-type cytochrome-dependent formation of U(IV) nanoparticles by *Shewanella oneidensis*. *PLoS Biol.* **4**, e268 (2006).
223 Schofield, E. J. *et al.* Structure of biogenic uraninite produced by *Shewanella oneidensis* strain MR-1. *Environ. Sci. Technol.* **42**, 7898-7904 (2008).
224 Lee, S. Y., Baik, M. H. & Choi, J. W. Biogenic formation and growth of uraninite (UO_2). *Environ. Sci. Technol.* **44**, 8409-8414 (2010).
225 Choudhary, S. & Sar, P. Identification and characterization of uranium accumulation potential of a uranium mine isolated *Pseudomonas* strain. *World J. Microbiol. Biotechnol.* **27**, 1795-1801 (2011).
226 Ohnuki, T. *et al.* Mechanisms of uranium mineralization by the yeast *Saccharomyces cerevisiae*. *Geochim. Cosmochim. Acta* **69**, 5307-5316 (2005).
227 Zheng, X. Y., Wang, X. Y., Shen, Y. H., Lu, X. & Wang, T. S. Biosorption and biomineralization of uranium(VI) by *Saccharomyces cerevisiae*-crystal formation of chernikovite. *Chemosphere* **175**, 161-169 (2017).
228 Huang, W. *et al.* Microscopic and spectroscopic insights into uranium phosphate mineral precipitated by *Bacillus mucilaginosus*. *ACS Earth Space Chem.* **1**, 483-492 (2017).
229 Zhang, J. *et al.* Immobilization of uranium at nanoscale by *Bacillus cereus* 12-2 at different U(VI) concentration. *J. Nanosci. Nanotechnol.* **19**, 7131-7138 (2019).