Supporting Information

From Microchannels to High Shear Reactors: Process Intensification Strategies for Controlled Nanomaterial Synthesis

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Table S1 Nomenclature

Abbreviation	Full name
PI	Process intensification
NM	Nanomaterial
NP	Nanoparticle
MCR	Microchannel reactor
STR	Stirred tank reactor
CIJR	Confined imping jet reactor
RPBR	Rotating packed bed reactor
HSM	High shear mixer
HSR	High shear reactor
SDR	Spinning disk reactor
UR	Ultrasonic reactor
MWR	Microwave reactor
FNP	Flash Nano-Precipitation

Table S2 Comparison of Different PI Technologies

	advantages	Micromixing time	Local turbulent kinetic energy dissipation rate	NP size management
MCR	Microscale effect, reducing particle size distribution, enhancing inter batch repeatability	2 ms[S1]	1×10^5 (W/kg)[S2]	66 nm[S3]
CIJR	Ultrafast mixing, high turbulence energy dissipation rate	0.2 ms[S4]	1×10^5 (W/kg)[S5]	142 nm[S6]
RPBR	Hypergravity field and high centrifugal force fields	0.053 ms[S7]	1.5×10^3 (W/kg)[S8]	60 nm[S9]
HSR	High shear rate and turbulence energy dissipation rate	0.101 ms[S10]	8×10^5 (W/kg)[S11]	7.09 nm[S12]
SDR	Centrifugal thin film, Promoting lateral mixing and reducing radial dispersion	0.38 ms[S13]	1×10^3 (W/kg)[S14]	47 nm[S15]

UR	Cavitation effect	Compared with the reactor without ultrasonic assistance, it is reduced by 1-2 orders of magnitude.	1×10^{9} (W/kg)[S16]	21 nm[S17]
MWR	Instantaneous and selective heating	Compared with the reactor without microwave assistance, it is reduced by 1-2 orders of magnitude.	4×10^{5} (W/kg)[S18]	2.6 nm[S19]

Table S3 Limitations of PI Technologies

	equipment service life	specific power consumption	Production	Scale-up readiness	Materials unsuitable for preparation	safety
MCR	Prone to fouling and clogging	10.46 W/kg[S20]	limited processing throughput	The number-up mode requires a large amount of manufacturing costs.	High-solid-content and high-viscosity materials	—
CIJR	Prone to fouling and clogging	160 W/kg[S21]	limited processing throughput	With amplification effect	High-solid-content and high-viscosity materials	—
RPBR	Prone to fouling and clogging	0.04 W/kg[S22]	limited processing throughput	—	High-solid-content and high-viscosity materials	—
HSR	—	4.61 W/kg[S23]	—	Prone to backmixing	Shear-sensitive materials	—
SDR	—	473 W/kg[S23]	limited processing throughput	—	—	—

UR	—	250 W/kg[S24]	—	With amplification effect	Heat-sensitive materials	local overheating caused by high-intensity cavitation effect
MWR	—	80 W/kg[S25]	—	With amplification effect	Heat-sensitive materials	local overheating caused by high-intensity microwave radiation

Table S4 Advanced applications of NMs manufactured by PI Technologies

Applications	Reactors	Nanomaterials	Advantages of reactors	Functions of PI-fabricated NMs	Ref
Biomedicine	CJI-CMR	CMC/Zn(II)/PAC nanoparticles	Fast and continuously producing a novel GHS in an energy-saving and safe way	Antibacterial and bacteriostatic	141
	CIJR	Poly(N-vinylcaprolactam) colloidal gels	Reducing gel size and improving stability	Stimuli-responsive	142
	RPBR	Oil dispersions of monodispersed $CaCO_3$ nanoparticles	Improving product quality and production efficiency	Used as overbased nanodetergents	143
	RPBR	Irbesartan nanoparticles	Reducing particle size, improving stability	Improving solubility/bioavailability	144
	SDR	Nimesulide nanoparticles	Reducing particle size, narrowing size distribution	Improving solubility/bioavailability	145
	UR	Zein-NaCas nanoparticles	Reducing the particle size, narrowing size distribution, improving encapsulation efficiency	Improving drug stability/solubility, providing a controlled release system	146

	USMR	PLGA-PEG, PLA/DDAB, mRNA-LNP nanoparticles	Reducing particle size, narrowing size distribution, improving production/encapsulation efficiency	Bioimaging	147
	HCR	O/W nanoemulsion	Reducing particle size, narrowing size distribution, improving stability	Increasing the release of nicotinamide	148
Adsorption	CJI-CMR	MSNs nanoparticles	Reducing particle size, increasing specific surface area and pore volume	Improving adsorption capacity/cycling stability of CO_2	149
	ICRPB	Zr-MOFs nanoparticles	Reducing reaction time and particle size, narrowing size distribution	Improving adsorption rate/capacity of water vapor	150
	IS-RPB	CMC-nZVI nanoparticles	Reducing particle size, narrowing size distribution, improving dispersibility	Improving adsorption capacity/removal efficiency of Pb^{2+}	151
	RPBR	D201-HFO-R nanocomposites	Reducing particle size, narrowing size distribution, improving dispersibility/production efficiency	Improving adsorption capacity/selectivity/cycling stability of Cr^{6+}	152
	MWR	CeO_2/MWCNTs nanocomposites	Reducing particle size, improving dispersibility	Improving adsorption capacity/removal efficiency of MB	153

	HSR	HSMSMs, HSMSMs-AO nano-meshes	Improving specific surface area/pore volume /chemical stability/mechanical strength/service life	Improving adsorption rate / capacity / selectivity of U^{6+}	154
	MW-MCR	Cu-BDC@rGO nanocomposites	Improving product quality/production efficiency	Improving adsorption capacity of H_2	155
	MWR	Th-MOF nanostructures	Improving specific surface area/pore volume /stability/dispersibility	Improving adsorption capacity/selectivity of CO and CH_4	156
	HSR	$CaCO_3$ (calcite)	Reducing the risk of blockage, improving removal efficiency of HCl and CO_2	Used as building material	157
Catalysis	RPBR	Cu-MnO_X/γ-Al_2O_3 nanocomposites	Improving the proportion of surface oxygen vacancies/oxide dispersibility/active species	Improving efficiency of ozonation/TOC removal	158
	UR	MnO_2/SnO_2 nanomaterials	Reducing particle size, improving specific surface area	Improving decomposition efficiency of H_2O_2	159
	HSR	CsCuHPAV nanoparticles	Reducing particle size, increasing specific surface area/acidic sites/active sites	Improving MAL conversion rate/MAA selectivity/ catalytic stability	160

	HSR	MnAl-MMO nanosheets	Reducing reaction temperature, improving specific surface area/pore volume/ pore size/acidic sites/active sites	Improving NO conversion rate/N_2 selectivity/catalytic stability	161
	UR	NiMo nanoparticles	Stabling metal ratio and reducing particle size	Improving hydrogenation efficiency /product quality/stability	163
	MWR	N-CQDs	Easy, economically affordable, and time-saving	Improving photocatalytic degradation efficiency of RB	164
	SDR	TiO_2, Cu- TiO_2 nanoparticles	Reducing particle size, narrowing size distribution/band gap energy	Improving CO_2 reduction efficiency and formate production rate	166
	SDR	AgNP-Z nanocomposites	Reducing particle size, improving dispersibility	Improving photocatalytic degradation efficiency of MB	167
	MIVM	$BiOCl_XBr_{1-X}$	Controllable synthesis, improving specific surface area, narrowing size distribution/band gap energy	Improving photocatalytic degradation efficiency of TC	165
Coatings	UR-HSR	PU nanocomposites	shortening of the mixing time, improving dispersibility	Improving adhesion strength and corrosion resistance	168

	UR	TiO_2: Fe_3O_4: Ag NMs	Reducing particle size, boosting the electron–hole pair separation, prolonging their recombination rate, improving dispersibility	Improving antibacterial and self-cleaning properties of fabrics, achieving controllable hydrophilicity/hydrophobicity	169
	UR	Protein-based nanoparticles containing vitamin E	Improving encapsulation efficiency/dispersibility	Improve antioxidant activity/stability/durability of fabrics	170
	UR	Ag, Au nanoparticles, fabric nanocomposites	Quick and environment-friendly, promoting the cleavage of glycosidic bonds and the formation of mechanical free radicals	Improve catalytic/antibacterial properties of fabrics	171
	MWR	Ag nanoparticles	Reducing particle size, improving dispersibility	Improving water absorption / antibacterial /UV-shielding properties of fabrics	172
	HSR	ZnO nanoparticles	Reducing particle size, narrowing size distribution, improving dispersibility	Improving the smoothness / antibacterial /anti-corrosion properties of the film	173
	UR	AgI/TiO_2 nanocomposites	Efficient and facile, reducing particle size, enhancing visible light absorption intensity	Improving the degradation efficiency /antibacterial activity of methyl orange	174

	UR	ZnO-PMMA hybrid nanoparticles	Improving dispersibility	Inhibiting corrosion of MS	175
	MCR	LNS	Reducing particle size, improving stability/ dispersibility	Improving UV-shielding efficacy of composite films	176
	RPBR	MHT nanoparticles	Reducing particle size, improving production efficiency	Improving the flame retardancy and thermal stability of composite materials	177
Optics	HCMR	SnO_2 nanoparticles	Reducing particle size, improving crystallinity	Reducing PL intensity, red shift in absorption edge and band gap energy	178
	RPBR	MgAl-LDH nanoparticles	Reducing reaction time/particle size, narrowing size distribution, improving dispersibility	Improving visual transparency	179
	HSR	ZnO nanoparticles	Reducing particle size, improving specific surface area/dispersibility	Improving photocatalytic degradation efficiency of MB	180
	HSR	$Sn_xZn_{1-x}O_{1+x}$ nanoparticles	Accelerating internal energy/nucleation rate Reducing particle size, Improving dispersibility	Improving photocatalytic degradation efficiency of MB	181

	UR	$YbVO_4$ nanostructure, $YbVO_4/CuWO_4$ nanocomposites	Reducing particle size, improving stability	Improving photocatalytic degradation efficiency/ cycling stability of MB	182
	CJIR	4CzIPN-DAE nanoparticles	Reducing reaction time/particle size	Improving efficiency of FRET/switchable fluorescence response	183
	MWR	Ag:PbS nanoparticles	Reducing particle size, improving stability/dispersibility	Reducing PL intensity, improving properties of electrical/dielectric/optoelectrical	185
	MWR	Ti_3C_2-MQDs	Reducing reaction time	Improving FRET efficiency/switchable fluorescence response/photodetector performance	186
	MWR	CuNWs/ZnS nanocomposites	In situ synthesis, improving metal dissolution/Cu^+ diffusion narrowing band gap energy	Improving photocatalytic degradation efficiency/ cycling stability of H_2 evolution, Improving H_2 evolution rate/apparent quantum efficiency	187
Electrochemistry	C-CFMCR	$KMnF_3$ nanoparticles	Reducing particle size, Improving dispersibility	Used as a supercapacitor, improving discharge specific capacitance, Improving	191

			density of current/energy/power/cycling stability	
MISR	Ni-Co-O nanocomposites	Reducing particle size, Improving specific surface area/pore volume/dispersibility	Used as a supercapacitor, improving specific capacitance/energy density/ power density/cycling stability	192
CJI-CMR	NiAl-LDH nanoparticles	Developing a rapid and continuous flow methodology for one-pot, in situ formation, adjusting layer spacing	Used as a supercapacitor, improving specific capacitance/ energy density/ power density/cycling stability	193
HSR	$LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$ nanoparticles	Reducing particle size, narrowing size distribution, improving dispersibility	Used as cathode material for Li^+ battery, improving discharge capacity/cycling stability	66
HSR	$LiNi_{0.60}Mn_{0.40}O_2$, $LiNi_{0.60}Mn_{0.40-x}Fe_xO_2$ nanoparticles	Improving Li^+ layer spacing, reducing Li^+ migration energy barrier	Used as cathode material for lithium-ion battery, reducing electrical impedance, Improving discharge capacity	194
HSR	$LiNi_{0.6}Co_{0.198}Mn_{0.2}La_{0.002}O_2$ nanoparticles	Reducing reaction time, improving dispersibility/ Li^+ layer spacing, reducing Li^+ migration energy barrier	Used as cathode material for Li^+ battery, improving discharge capacity/cycling stability	195

	SDR	Prussian blue nanoparticles	Low-cost and efficient, reducing defects, increasing Na^+ content	Used as cathode material for Na^+ battery, improving discharge capacity/cycling stability	196
	SDR	Sulfur nanoparticles, S-TiO_2 Core–Shell Powder	Reducing particle size, narrowing size distribution, Improving production efficiency	Used as cathode material for Li^+ battery, improving discharge capacity/cycling stability	197
	UR	SbSI nanowires, SbSI-PAN nanocomposites	Realizing at mild conditions in a simple and fast way	Used as a photovoltaic device, improving open circuit voltage and short circuit photocurrent density	198

Table S5 Comparison between Traditional Methods and PI Technologies

Applications	Materials and parameters	Comparison	
Biomedicine	GHS with CMC/Zn(II)/PAC nanoparticles	STR	CJI-CMR
	Alcohol content	63.8 vol%	68.4 vol%
	Oil dispersions of monodispersed $CaCO_3$ nanoparticles	STR	RPBR
	Particle size	9.4 nm	5.9 nm
	Total base number	397 mg KOH/g	405 mg KOH/g
	Carbonation reaction time	120 min	53 min
	Storage stability	12 months	18 months
	Residue	>6%	2.5%
	Irbesartan nanoparticles	STR	RPBR
	Particle size	5–20 μm	295 nm
	Specific surface area	3.51 m^2/g	23.87 m^2/g
	Saturation solubility	3.6 μg/mL	13.7 μg/mL
	Dissolution rate (30 min)	12%	100%
	Nimesulide nanoparticles	STR	SDR
	Particle size	13.10 μm	192 nm

	raw drug	SDR
Dissolution time (100% release)	180 min	80 min
Zein- sodium caseinate (Zein-NaCas) nanoparticles	Without UR	UR
Particle size	327.23 µm	228.21 nm
Encapsulation efficiency	76.84 ± 0.16%	90.19 ± 0.33%
DPPH scavenging ability	58.58 ± 2.69%	79.01 ± 4.26%
Cur retention rate at 75℃ (thermal stability)	58 ± 0.52%	85.26 ± 0.61%
Cumulative release rate (after 90 min of digestion in simulated gastric fluid)	19.72 ± 2.19%	16.63 ± 1.46%
Cumulative release rate (after 240 min of digestion in simulated intestinal fluid)	70.46 ± 2.12%	48.26 ± 1.48%
PLGA-PEG nanoparticles	microfluidics method	USMR
Particle size	137 nm	85 nm
	ultrasound-based method	USMR
PDI	0.21	0.09
Oil-in-water (O/W) nanoemulsion	STR	HCR
Cumulative release of nicotinamide (12 h)	3545.4 µg/cm^2	4335.8 µg/cm^2

	Droplet size	1879 nm	366.4 nm
		3D-printed	HCR
	The cost of the rotor	600 USD	2 USD
Adsorption	MSNs nanoparticles	Without CJI-CMR (SBA-15)[S26]	CJI-CMR (MSNs nanoparticles)
	Specific surface area	507 m^2/g	1854 m^2/g
	Pore size	8.5 nm	3.3 nm
	Li_4SiO_4	Without CJI-CMR (diatomite-Li_4SiO_4)[S27]	CJI-CMR (US1854-Li_4SiO_4-Li/Si = 4.5)
	Adsorption capacity (CO_2, 700°C)	16%	34.1%
	Zr-MOFs nanoparticles	STR	ICRPB
	Reaction time (90°C)	43 min	23 min
	Particle size (90°C)	172 ± 40 nm	134 ± 16 nm
	Size distribution (90°C)	40 nm	16 nm
	UiO-66	without ICRPB	with ICRPB
	Specific surface area[S28]	1335 m^2/g	1416 m^2/g
	Adsorption capacity (water vapor)[S28]	576 mg/g	625 mg/g

CMC-nZVI nanoparticles	Without IS-RPB (CS@nZVI-CMC nanocomposite)	With IS-RPB (CMC-nZVI nanoparticles)
Removal (Pb(II))[S29]	52.73%	80.00%
D201-HFO-R nanocomposites	STR (D201-HFO-S2)	RPBR (D201-HFO-R)
Particle size	18.45 nm	10.34 nm
Fe content	3.85%	4.21%
Specific surface area	16.24 m^2/g	17.31 m^2/g
Pore volume	0.29 cm^3/g-	0.31 cm^3/g
Pore diameter	26.53 nm	29.98 nm
Rate constant	0.90 /min	0.959 /min
Reaction time	12 h	45 min
HSMSMs nano-meshes	Without HSR (SBA-15)	HSR (HSMSM)
Adsorption capacity (U(IV))[S30]	401 mg/g	822 mg/g
HSMSMs-AO nano-meshes	Without HSR (NH_2-H-SBA-15)	HSR (HSMSMs-AO)
Adsorption capacity (U(IV))[S31]	780 mg/g	877 mg/g
Cu-BDC@rGO nanocomposites	conventional heating method	MW-MCR
Production yield		Improving 18%

	Adsorption capacity (H_2)		Improving 26%
	Th-MOF nanostructures	UR (UARM)	MWR (MARM)
	Particle size	84 nm	18 nm
	Decomposition temperature	235℃	290℃
	Specific surface area	1439 m^2/g	2240 m^2/g
	Pore diameter	2.7 nm	1.4 nm
	Adsorption capacity (CH_4)	177 v/v	255 v/v
Catalysis	Cu-MnO_X/γ-Al_2O_3 nanocomposites	STR	RPBR
	Reaction time	6 h	45 min
	Pore diameter	7.8 nm	9.5 nm
	Molar ratio (Cu^0/Cu^+)	1.08	1.24
	Molar ratio (Mn^{4+}/Mn^{3+})	0.50	0.76
	The cover area ratio of O^{2-}/O_{surf} species	0.60	1.34
	Ph_{pzc}	7.0	5.7
	MnO_2/SnO_2 nanomaterials	Without UR	UR
	Particle size	32.0 nm	5.2 nm
	Specific surface area	41.7 m^2/g	78.6 m^2/g

Pore volume	0.077 cm^3/g-	0.118 cm^3/g
Decomposition efficiency (H_2O_2)	37.5%	84.4%
$CsCu_{0.1}H_{2.9}PMo_{11}VO_{40}$ nanoparticles	Without HSR	HSR
Particle size	35.6 nm	24.3 nm
Specific surface area	7.5 m^2/g	30.9 m^2/g
Pore volume	42.3×10^{-3} cm^3/g-	77.8×10^{-3} cm^3/g
Total number of acid sites	0.74 $mmol/g_{cat}$	1.13 $mmol/g_{cat}$
Intercrystallite void	41.6×10^{-3} cm^3/g	73×10^{-3} cm^3/g
Surface ratios (V(IV))	0.38	0.5
Conversion efficiency (MAL)	70%	83%
Selectivity efficiency (MAA)	80%	87%
Production yield (MAA)	68.3%	73.1%
Turnover frequency		Improving 30%-70%
MnAl-MMO nanosheets	Without HSR	HSR
Particle size	909.1 nm	234.8 nm
Specific surface area	125.3 m^2/g	180.6 m^2/g
Pore volume	0.27 cm^3/g-	0.45 cm^3/g

Pore diameter	8.9 nm	9.8 nm
Mn^{4+}/Mn	22.36%	29.19%
$O_\alpha/(O_\alpha + O_\beta)$	47.53%	57.59%
Conversion efficiency (NO) (25℃)	14%	39%
Conversion efficiency (NO) (5 vol% H_2O) (200℃)	91% → 60%	98% → 90%
Conversion efficiency (NO) (5 vol% H_2O + 100 ppm SO_2) (After stopping the injection) (200℃)	85%	70%
NiMo nanoparticles	HSR	UR
Particle size	70.2 nm	30.7 nm
Ni/(Ni + Mo)	0.383	0.374
API density of the feed	4°→ 8.1°	3.4°→ 10.1°
Viscosity reduction	98.6%	99.4%
De-metallization of Ni	44.8 %	54.5 %
Lowest P-value	1.9	2.2
TiO_2 nanoparticles	Batch mode	SDR
PDI	0.88	0.23–0.55
Production rate (formate)		Improving 15–21%

	$BiOCl_XBr_{1-X}$	Without MIVM	MIVM
	Morphology	uneven flower-like shape	Uniform petal-like shape
	Particle size	>1 µm	523 nm
Coatings	lignin	Without MCR (raw lignin)	MCR (lignin nanoparticles)
	Particle size	2-10 µm	10–20 nm
	Morphology	Irregular shape	spherical-like shape
	PVA	PVA film with raw lignin	PVA film with lignin nanoparticles
	Morphology	Relatively matte	smooth and homogeneous
	UV-shielding efficacy		Improving 13%
	MHT nanoparticles	Without RPBR ($MgAl-CO_3$)	RPBR (MHT-3)
	Particle size[S32]	1-120 µm	160 nm
	MgAl-LDH nanoparticles	STR (800 rpm)	RPBR (2400 rpm)
	Reaction time	20 min	20 s
	Particle size	57 nm	31 nm
	Production yield	5.25 g/h	315 g/h

	Visible-light transmittance (555 nm)	66.5%	77.4%
	ZnO nanoparticles	STR (ZnO-M)	HSR (ZnO-HSS)
	Particle size	9.69 nm	7.09 nm
	Medium particle sizes	531 nm	26.5 nm
	Photocatalytic degradation efficiency of MB (30 min)	38.6%	70.8%
		STR (ZnO-L)	HSR (ZnO-HSS)
	Formation time (phenomenon B) of zno		faster 52 times
	Exposed surface area		Larger 2.15 times
	$Sn_xZn_{1-x}O_{1+x}$ nanoparticles	STR	HSR
	Molecular velocity	3 m/s	290 m/s
	Molecules internal energy	0.81 eV	174 eV
	Particle size	68.06 nm	50.75 nm
	Bandgap (after incorporating 5 % Sn)	3.25 eV	3.04 eV
	Photocatalytic degradation efficiency of MB ($Sn_{0.05}Zn_{0.95}O_{1.05}$)		Improving 12.2%
	Photocatalytic degradation efficiency of MB ($Sn_{0.15}Zn_{0.85}O_{1.15}$) (120 min)	19.3%	9.61%
	$YbVO_4$ nanostructure	Without UR	UR

	Photocatalytic degradation efficiency of MB	61%	100%
Electrochemistry	Ni-Co-O nanocomposites	STR	MISR
	Specific surface area	56.9 m²/g	65.9 m²/g
	Specific capacitance (1 A/g)[S33]	671 F/g	2012 F/g
	Energy density[S34]	33.4 Wh/kg	48.3 Wh/kg
	$LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$ nanoparticles	STR (CI-1100)	HSR (HSM-3-10000)
	Particle size	0.817 μm	0.310 μm
	Discharge capacity (32 ma/g)	155.8 mAh/g	181.1 mAh/g
	Cycling stability (3200 ma/g)	42.2%	83.7%
	Charge transfer resistance	308.9 Ω	117.4 Ω
	Li^+ diffusion coefficients	1.03×10^{-15} cm^2/s	3.51×10^{-14} cm^2/s
	Prussian blue nanoparticles	Without SDR (C-PB)	SDR (R-PB)
	Particle size	100–120 nm	60–80 nm
	Na	10.32%	13.86%
	Sulfur nanoparticles	Without SDR	SDR
	Particle size	580–600 nm	50-70 nm
	Initial capacity	570 mAh/g	1510 mAh/g

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