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Carbon nitride nanotubes-based materials for energy and environmental applications: A review of recent progress

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Table S1 Representative summary of photocatalytic H_2 production over CNNTs-based photocatalysts

Catalyst	Dopant /loaded material	Mass of photocatalyst, reaction solution and cocatalyst	Light source	Activity (μmol h^{-1})	Reference material and its activity (μmol h^{-1})	Stability	AQE (%)	Ref.
CNNTs	/	10 mg, 120 mL, 10 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 75.05	CN nanosheets H_2: 12.36	15 h	19.20 (400 nm)	1
CNNTs	/	20 mg, 20 mL, 10 vol.% TEOA, Pt (1 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 321.42	Bulk CN H_2: 65.60	16 h	/	2
CNNTs	/	100 mg, 100 mL, 10 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ > 400 nm)	H_2: 28.50	Bulk CN H_2: 24.60	/	/	3
CNNTs	/	50 mg, 50 mL, 10 vol.% TEOA, Pt (3 wt.%)	50 W White LED	H_2: ~12.60[b]	Bulk CN H_2: ~5.40[b]	20 h	1.30 (525 nm)	4
CNNTs	/	50 mg, 100 mL, 10 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ > 400 nm)	H_2: 207.90	Bulk CN H_2: 12.30	16 h	/	5
Porous CNNTs	/	50 mg, 100 mL, 10 vol.% TEOA, Pt (5 wt.%)	Xe lamp[a] (λ > 400 nm)	H_2: 70.6	Bulk CN H_2: 4.70	/	/	6
Porous CNNTs	/	20 mg, 20 mL, 20 vol.% lactic acid, Pt (0.5 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 21.47	Bulk CN H_2: 4.58	20 h	2.81 (420 nm)	7
Porous CNNTs	/	50 mg, 333 mL, 10 vol.% methanol, Pt (1 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 8.87	Bulk CN H_2: 1.40	/	/	8
Porous CNNTs	/	10 mg, 100 mL, 10 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 15.40	CN sheets H_2: 5.50	20 h	1.10 (420 nm)	9
Mesoporous CNNTs	/	50 mg, 100 mL, 10 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 439.45	Bulk CN H_2: 81.70	15 h	6.30 (420 nm)	10
Nitrogen-rich CNNTs	/	10 mg, 100 mL of TEOA (10 vol.%), Pt (1 wt.%)	Xe lamp[a] (λ > 400 nm)	H_2: 180.62	Bulk CN H_2: 9.27	16 h	12.55 (420 nm)	11
CN tubes	/	50 mg, 100 mL, 10 vol.% lactic acid, Pt (1 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 67.70	Bulk CN H_2: 11.28	24 h	14.30 (420 nm)	12
Prismatic CNNTs	/	40 mg, 90 mL, 10 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 138.72	Bulk CN H_2: 18.88	20 h	10.86 (420 nm)	13
Thin-walled CNNTs	/	100 mg, 100 mL, 10 vol.% TEOA, Pt (1 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 399	Bulk CN H_2: 10.50	48 h	8.70 (420 nm)	14
PTYS	/	50 mg, 100 mL, 20 vol.% lactic acid, Pt (1 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 37	Bulk CN H_2: 6.15	16 h	11.80 (420 nm)	15
CN microtubes	/	50 mg 100 mL, 20 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 47.90	Bulk CN H_2: 2.56	25 h	0.60 (420 nm)	16
CN microtubes	/	50 mg, 20 mL, 20 vol.% lactic	Xe lamp[a] (λ > 420 nm)	H_2: 50	Bulk CN H_2: 16.13	15 h	/	17

		acid, Pt (0.5 wt.%)						
Hierarchical CNNTs	/	20 mg, 50 mL, 20 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 105.80[b]	Bulk CN H_2: 2.94[b]	25 h	32.40 (420 nm)	18
3D assemblies of CNNTs	/	10 mg, 100 mL, 20 vol.% methanol, Pt (1 wt.%)	Xe lamp[a] (AM1.5G)	H_2: 71	Bulk CN H_2: 6.30	16 h	7.40 (420 nm)	19
CNNTs with N and O defects	/	30 mg, 100 mL, 20 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 238.50	Bulk CN H_2: 17.10	15 h	8.32 (420 nm)	20
CNNTs with N defects	/	10 mg, 100 mL, 10 vol.% TEOA,	Xe lamp[a] (λ > 400 nm)	H_2: 118.50	Bulk CN H_2: 12	20 h	6.80 (420 nm)	21
P doped CNNTs	/	50 mg, 100 mL, 10 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 101	Bulk CN H_2: 4.50	10 h	4.32 (420 nm)	22
C doped CNNTs	/	30 mg, 100 mL, 10 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 32.30	Bulk CN H_2: 7.50	16 h	4.38 (420 nm)	23
P doped CNNTs with C defects	/	100 mg, 100 mL, 20 vol.% methanol, Pt (1 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 57	Bulk CN H_2: 6	12 h	/	24
Porous CNNTs with structural defects	/	50 mg, 100 mL, 10 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 261.80	Bulk CN H_2: 24.60	20 h	/	25
P doped CNNTs	/	10 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 4.59	Bulk CN H_2: 0.24	/	/	26
P doped-CNNTs	P (1.21 wt.%)	100 mg, 100 mL, 20 vol.% methanol, Pt (1 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 67	Bulk CN H_2: 9	20 h	5.68 (420 nm)	27
P/S co-doped CNNTs	/	10 mg, 100 mL, 10 vol.% TEOA, Pt,	Xe lamp[a] (λ > 400 nm)	H_2: 163.27	CN nanosheets H_2: 0.21	60 h	18.93 (420 nm)	28
Alkali metals implanted CNNTs	/	100 mg, 100 mL, 10 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 502	/	5 h	21.20 (420 nm)	29
Co doped CNNTs	/	30 mg, 50 mL, 25 vol.% TEOA, Pt (2 wt.%)	Xe lamp[a] (350-780 nm)	H_2: 22.25	Bulk CN H_2: 17.74	9 h	/	30
Na doped CNNTs	Na (0.10 wt.%)	20 mg, 100 mL, 10 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 143	Bulk CN H_2: 13	30 h	1.80 (420 nm)	31
Cu doped CNNTs	Cu (0.05 wt.%)	50 mg, 100 mL, 10 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 151	Bulk CN H_2: 11.85	/	/	32
NaCl doped CN microtubes	NaCl (3 wt.%)	10 mg, 30 mL, 17 vol.% TEOA, Pt (1 wt.%)	500 W Xe lamp (420 to 780 nm)	H_2: 4.95	Bulk CN H_2: 1.15	12 h	/	33
CNNTs with N defects	/	10 mg, 100 mL, 10 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 8.19	Bulk CN H_2: 0.21	16 h	1.90 (420 nm)	34
Pt-CNNTs	Pt (2 wt.%)	100 mg, 100 mL, 10 vol.% TEA,	Xe lamp[a] (λ > 420 nm)	H_2: 13.50	Bulk CN H_2: 2.25	/	/	35
Pt@Au/CNNTs	Pt@Au Au: 2.4 wt.%	20 mg, 100 mL, 10 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 207	CNNTs No H_2 generated	20 h	9.10 (420 nm)	36
Ag-Cu/CNNTs	Ag_1-Cu_1 (15 wt.%)	40 mg, 40 mL, 10 vol.% TEA,	Xe lamp[a] (λ > 420 nm)	H_2: 4.15	Bulk CN H_2: 1.83	12 h	/	37
Pt-Ni/CNNTs	Pt_1-Ni_1	50 mg,	Xe lamp[a]	H_2: 104.70	CNNTs	25 h	5.89	38

	(1 wt.%)	100 mL of TEOA (10 vol.%)	(λ > 420 nm)		H_2: 2.20		(420 nm)	
I/N-CNNTs	/	10 mg, 100 mL, 10 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ ≥ 420 nm)	H_2: 9.75	CNNTs H_2: 2.68	16 h	4.14 (420 nm)	39
Isotype CNNTs	/	40 mg, 90 mL, 11 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 63	Bulk CN H_2: 9	/	/	40
K^+, cyano groups/CNNTs	/	100 mg, 100 mL, 10 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 66.10	Bulk CN H_2: 5.51	16 h	2.88 (420 nm)	41
Transitional metal ions/CNNTs	Fe^{3+} (15.64 mg/kg)	20 mg, 100 mL, 20 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 150.76	CN nanosheets H_2: 11.15	12 h	1.10 (420 nm)	42
Uio-66-NH_2/CNNTs	Uio-66-NH_2 (16.7 wt.%)	50 mg, 100 mL, 10 vol.% TEOA, Pt (1 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 152.20	CNNTs H_2: 89.53	25 h	/	43
CdS/CNNTs	CdS (10 mol.%)	100 mg, 100 mL, 10 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ ≥ 420 nm)	H_2: 71.60	Bulk CN H_2: 4.39	25 h	/	44
MoS_2/CNNTs	MoS_2 (15 wt.%)	200 mg, 100 mL, 20 vol.% TEOA,	Xe lamp[a] All spectrum	H_2: 224.80	Bulk CN H_2: 12.80	12 h	2.34 (420 nm)	45
CeO_2/S-CNNTs	CeO_2 (10 wt.%)	50 mg, 100 mL, 20 vol.% TEOA, Pt (1 wt.%)	300 W Xe lamp[a] (λ > 400 nm)	H_2: 146.19	S-CNNTs H_2: 73.31	14 h	/	46
CoO/CNNTs	CoO (7 wt.%)	40 mg, 40 mL, 10 vol.% TEOA,	Xe lamp[a] (λ > 420 nm)	H_2: 10.51	Co_3O_4/CNNTs H_2: 9.67	12 h	4.93 (420 nm)	47
Fe_2O_3/N rich CNNTs	Fe_2O_3 (3.33 wt.%)	10 mg, 100 mL of water, Pt (1 wt.%)	Xe lamp[a] (1.5G filter)	H_2: 3.70	N rich CNNTs H_2: 1.20	16 h	7.10 (365 nm)	48
C/N-TiO_2@CNNTs	C/N-TiO_2	100 mg, 100 mL, 20 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ> 420 nm)	H_2: ~48.33[b]	C-TiO_2@CNNTs H_2: ~28.33[b]	/	/	49
CdS/P-CNNTs	CdS (1 wt.%)	10 mg, 100 mL, 0.35 M Na_2S and 0.35 M Na_2SO_3	Xe lamp[a] (λ > 420 nm)	H_2: 15.79	CdS/CNNTs H_2: 5.14	15 h	/	50
NYFG/CNNTs	NYFG (15 wt.%)	40 mg, 40 mL, 10 vol.% TEA,	980 nm diode laser	H_2: 4.15	NYF/CNNTs H_2: 2.94	12 h	0.08 (980 nm)	51
CQD/CNNTs	Carbon QDs	50 mg, 100 mL, 20 vol.% methanol, Pt (~3 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 176.92	Bulk CN H_2: 71.93	20 h	10.94% (420 nm)	52
C-Dots/CNNTs	C-Dots	50 mg, 330 mL, 10 vol.% methyl alcohol, Pt (1 wt.%)	Xe lamp[a] (λ ≥ 420 nm)	H_2: 1238	CNNTs H_2: 10.95	18 h	21.20 (420 nm)	53
Graphene QDs/CNNTs	QDs (0.15 wt.%)	100 mg, 100 mL, 20 vol.% of methanol, Pt (1 wt.%)	Xe lamp[a] (λ > 420 nm)	H_2: 112.10	Bulk CN H_2: 11.80	20 h	/	54
C-PAN/CNNTs	C-PAN (5 wt.%)	100 mg, 150 mL, 10 vol.% TEOA, Pt (3 wt.%)	Xe lamp[a] (λ > 400 nm)	H_2: 177.50	Bulk CN H_2: ~10.63[b]	15 h	5.60 (420 nm)	55

[a] Xe lamp has a power of 300 W. [b] estimated from the published H_2 performance curve in the literatures. TEOA: triethanolamine. TEA: triethylamine.

Table S2 Representative summary of photocatalytic pollutant degradation over CNNTs-based photocatalysts

Catalyst	Dopant /loaded material	Mass of photocatalyst and pollutant conditions	Light source	Activity (rate constant, *k*)	Reference photocatalyst and its activity (rate constant, *k*)	Ref.
AgCl/CNNTs	AgCl (20 wt.%)	50 mg, 50 mL, 0.2 mM RhB,	350 W Xe lamp Visible light	0.02827 min^{-1}	Bulk CN, 0.01134 min^{-1}	56
Fe^{3+} modified CNNTs	Fe^{3+} (15.64 mg/kg)	30 mg, 50 mL, 10 mg/L RhB	300 W Xe lamp (λ ≥ 420 nm)	In 35 min, degraded 100%	CN nanosheets In 60 min, degraded 60%	42
CNNTs	/	50 mg, 100 mL, 10 mg/L RhB	500 W Xe lamp (λ > 400 nm)	0.00638 min^{-1}	/	6
CNNTs	/	20 mg, 20 mL, 20 mg/L MO or TC	300 W Xe lamp (λ > 400 nm)	MO: in 70 min, degraded 100% TC: in 180 min, degraded 92.70%	CN nanosheets MO: in 70 min, degraded 21.60% TC: in 180 min, degraded 61.8%	1
CNNTs	/	10 mg, 10 mL, 20 mg/L RhB	50 W LED white light (λ > 410 nm)	In 30 min, degraded ~98%[a]	CN nanosheets In 30 min, degraded ~82%[a]	57
CNNTs	/	5 mg, 100 mL, 4 mg/L RhB	500 W Xe lamp (λ ≥ 420 nm)	0.06 min^{-1}	Bulk CN 0.005 min^{-1}	58
CNNTs	/	100 mg, 100 mL, 10 mg/L RhB	Xe lamp (λ > 400 nm)	0.074 min^{-1}	Bulk CN 0.021 min^{-1}	3
CNNTs	/	5 mg, 5 mL, 10 μg/Ml RhB	12 W LED at 420 nm	In 105 min, degraded 100%	Bulk CN In 105 min, degraded < 20%	59
CNNTs	/	50 mg, 100 mL, 10 mg/L RhB	300 W Xe lamp (λ> 420 nm)	0.01 min^{-1}	Bulk CN 0.007 min^{-1}	60
CNNTs	/	100 mg, 40 mL, 10 mg/L MB or MO	500 W Xe lamp Visible light	MB: 0.02116 min^{-1} MO: 0.0067 min^{-1}	Bulk CN MB: ~0.015 min^{-1}[a] MO: ~0.005 min^{-1}[a]	61
CNNTs	/	50 mg, 100 mL, 10 mg/L MO	300 W Xe lamp (λ > 400 nm)	In 120 min, degraded 84%	Bulk CN In 120 min, degraded 19%	62
Prismatic CNNTs	/	10 mg, 50 mL, 10 mg/L RhB	500 W Xe lamp (λ > 420 nm)	0.05032 min^{-1}	Bulk CN 0.00342 min^{-1}	13
Isotype CNNTs	/	30 mg, 30 mL, 10 mg/L MO	500 W Xe lamp (λ > 420 nm)	0.0127 min^{-1}	Bare CNNTs 0.0079 min^{-1}	40
Ag/CNNTs	Ag (1 wt.%)	200 mg, 100 mL, 20 mg/L MO,	300 W Xe lamp (λ > 420 nm)	0.55909 min^{-1}	Bare CNNTs 0.22399 min^{-1}	63
C/X-TiO_2@CNNTs (X= N, F, Cl)	/	100 mg, 100 mL, 10 mg/L MO, or 20 mg/L PCP	300 W Xe lamp (λ > 420 nm)	In 120 min MO: C/F-TiO_2@CNNTs degraded ~72%[a], PCP: C/Cl-TiO_2@CNNTs degraded ~86%[a]	Bulk CN In 120 min MO: degraded ~10%[a], PCP: degraded ~12%[a]	49
$H_3PW_{12}O_{40}$/CNNTs	$H_3PW_{12}O_{40}$ (30 wt.%)	200 mg, 100 mL, 10 mg/L MO or DEP	300 W Xe lamp (λ > 420 nm)	MO: in 4 h, degraded ~100%[a], DEP: in 24 h, degraded ~84%[a]	Bulk CN MO: in 4 h, degraded ~38%[a], DEP: in 24 h, degraded ~20%[a]	64
CNNTs	/	50 mg, 50 mL MO or ERB or AR18	300 W Xe lamp (λ > 400 nm)	In 3 h, MO, ERB, ERB: degraded ~85%[a], ~90%[a], ~100%[a]	/	65
Nitrogen-rich CNNTs	/	20 mg, 100 mL, 10 mg/L BPA simultaneous with H_2 production system 25 mg, 50 mL, 10 mg/L MB	300 W Xe lamp (λ > 400 nm)	BPA: in 120 min, degraded ~70% MB: in 210 min, degraded ~49%[a]	Bulk CN BPA: in 120 min, degraded ~33%, MB: in 210 min, degraded ~17%[a]	11
Porous CNNTs	/	10 mg, 30 mL, 30 mg/L TC	300 W Xe lamp (λ > 420 nm)	0.1471 min^{-1}	CN nanosheets 0.1471 min^{-1}	9

CNNTs with defects	/	25 mg, 50 mL, 10 mg/L MB	300 W Xe lamp (λ > 400 nm)	0.0077 min^{-1}	Bulk CN 0.0009 min^{-1}	21
Pt/CNNTs	Pt (2 wt.%)	100 mg, 100 mL, 20 mg/L PCP	300 W Xe lamp (λ > 420 nm)	In 7 h, degraded ~98%[a]	Bulk CN In 7 h, degraded ~35%[a]	35
B modified CNNTs	/	50 mg, 100 mL, 10 mg/L RhB or MB	300 W Xe lamp (λ > 420 nm)	In 90 min, RhB, MB: degraded 99.30%, 98.90%	Bulk CN In 90 min, RhB, MB: degraded 48.20%, 51.80%	66
S-CQDs/CNNTs	S-CQDs 0.2 mg	1 g/L, 20 mg/L TC	300 W Xe lamp (visible light)	0.0293 min^{-1}	Bulk CN 0.0059 min^{-1}	67
Z-Scheme CNNTs	/	25 mg, 50 mL, 10 mg/L DON	300 W Xe lamp (λ ≥ 420 nm)	0.001667 min^{-1}	Bulk CN 0.0004167 min^{-1}	68
Carbon QDs/CNNTs	/	25 mg, 50 mL, 1 mg/L CBZ	Xe lamp (λ > 400 nm)	0.0568 min^{-1}	Bare CNNTs 0.0136 min^{-1}	69
BP/CNNTs	/	30 mg, 50 mL, 10 mg/L OTC-HCl, 50 mg, 50 mL, 10 mg/L Cr(VI)	Xe lamp (λ > 420 nm)	OTC-HCl: 0.0276 min^{-1} Cr(VI): 0.0276 min^{-1}	Bare CNNTs OTC-HCl: 0.0117 min^{-1} Cr(VI): 0.0276 min^{-1}	70
CNNTs	/	100 mg, 600 ppb NO	30 W LED (Visible light)	Removal rate: 59.40%	CN nanosheets Removal rate: 40.17%	71
B doped CNNTs	H_3BO_3 2 mmol	100 mg, 400 ppb NO	300 W Xe lamp (λ > 420 nm)	Removal rate: 30.40%	Bulk CN Removal rate: 20.80%	72
CNNTs with C vacancies	/	200 mg, 50 ppm NO	LED lamp (λ ≥ 448 nm)	Removal rate: 47.70%	/	73
CNNTs with N and O defects	/	100 mg, 400 ppm NO	300 W Xe lamp (λ ≥ 420 nm)	Removal rate: 81.97%	Bulk CN Removal rate: 16.02%	20

[a] estimated from the figures in the literatures.

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