Supplementary Information for
Nelumbo Nucifera (Lotus)-Floral Waste assisted Enhanced and Sustainable Photocatalytic Hydrogen Generation

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S1. Physiochemical characterizations

All the physiochemical properties of the NN-ZnO powder samples have been characterized using several characterization tools. The crystallinity and morphology of the materials have been examined using XRD (X'Pert3 powder and Empyrean, PANalytical), SEM-EDX (Hitachi S-3400, 15.0 KV, WD: 5.5 mm) and HR-TEM and SAED pattern (JEOL F-200 multipurpose electron microscope; 200 kV). The zeta potential and particle size of the samples have been measured in a disposable folded capillary cell on a Malvern Zetasizer Nano Z zeta potential analyzer. The chemical bonds of the materials have been investigated using FTIR (PerkinElmer Spectrum-2 Imaging System). The optical properties of the materials have been examined using UV-Vis (Perkin Elmer Lambda 365 UV/ Vis Spectrophotometer) in the wavelength range of 200-800 nm and photoluminescence spectra have been investigated using Horiba FluoroMax Plus (1700 nm, 25 ps). X-ray Photo electron Spectroscopy (XPS) with Al Ka irradiation have been used to study the surface elemental interactions using Model AXIS Supra. The nitrogen adsorption and desorption isotherms, specific surface area and porosity characteristics of samples have been obtained to identify the surface area using porosity analyzer (Quantachrome TouchWin) at 77.3 K. The specific surface area has been evaluated by Brunauer-Emmett-Teller (BET). Thermogravimetric analysis has been performed on PerkinElmer TGA 4000 at a scan rate of 20°C up to a temperature of 850°C.

Table S1 Details of solar simulator

Newport Oriel LCS-100 (Class ABB)	Lamp type	Xenon 100 W
	Output beam size	38 x 38 mm
	Beam divergence, half angle	<6°
	Typical output power	1.0 sun (100 mW/ cm^2)
	Output intensity measurement	Newport 843-R

S2. Additional results

XRD analysis

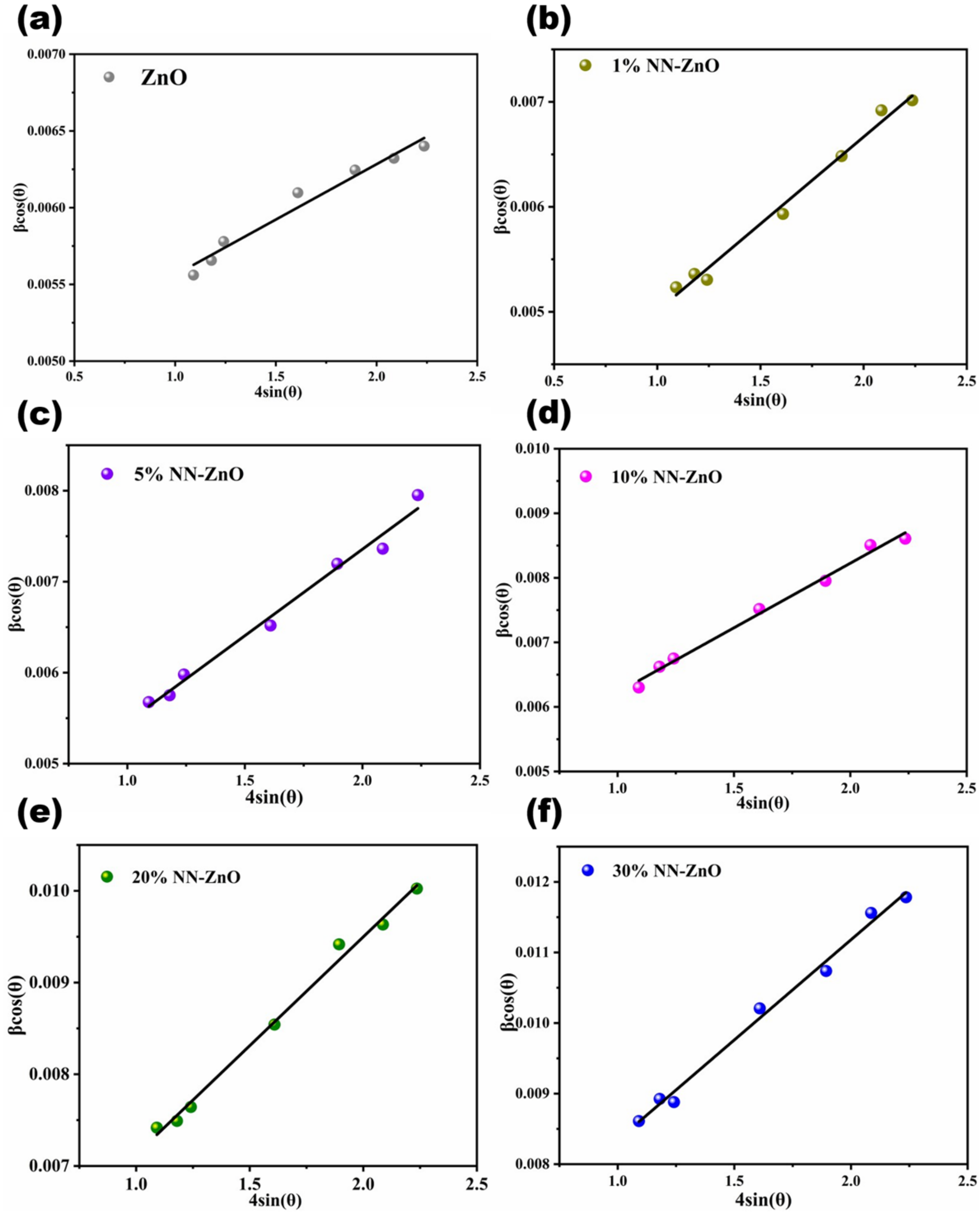

Fig. S1. W-H plots of all the percentage variations of NN-ZnO along with pristine ZnO.

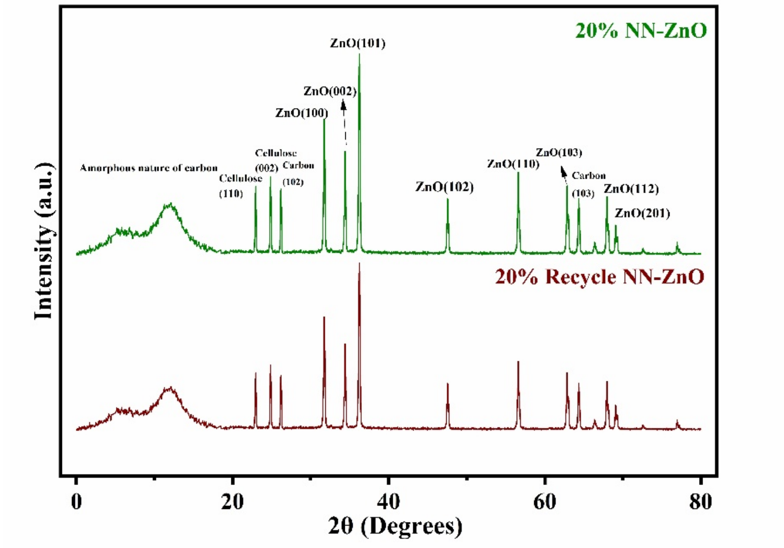

Fig. S2. Comparison analysis between XRD plots of fresh and used photocatalyst after 4-consecutive hydrogen generation cycles

Table S2 Average particle size calculation using Scherrer's equation

K	λ (nm)	Peak position 2θ (°)	$FWHM\ \beta$ (°)	$FWHM\ \beta$ (radian)	cos(2θ/	D (nm)	θ	Average D (nm)
0.94	0.15406	31.659	0.1489	0.0026	0.962	57.950	15.83	45.56
		34.315	0.1582	0.0028	0.955	54.920	17.16	
		36.148	0.1641	0.0029	0.951	53.215	18.07	
		47.442	0.2009	0.0035	0.916	45.135	23.72	
		56.506	0.2287	0.0040	0.881	41.209	28.25	
		62.883	0.2956	0.0052	0.853	32.917	31.44	
		67.973	0.2978	0.0052	0.829	33.620	33.99	

SAED pattern analysis

Table S3 Value of d-spacing and indexing results of SAED patterns analysis

Serial number	$1/D$ (nm^{-1})	$1/r$ (nm^{-1})	r (nm)	d-spacing (Å)	(hkl)
1	7.091	3.545	0.282	2.820	(100)
2	7.677	3.838	0.261	2.605	(002)
3	8.105	4.052	0.247	2.468	(101)
4	10.456	5.228	0.191	1.913	(102)
5	12.347	6.173	0.162	1.619	(110)
6	13.540	6.770	0.148	1.478	(103)
7	14.485	7.242	0.138	1.381	(112)
8	14.762	7.381	0.135	1.355	(201)

Particle size and zeta potential

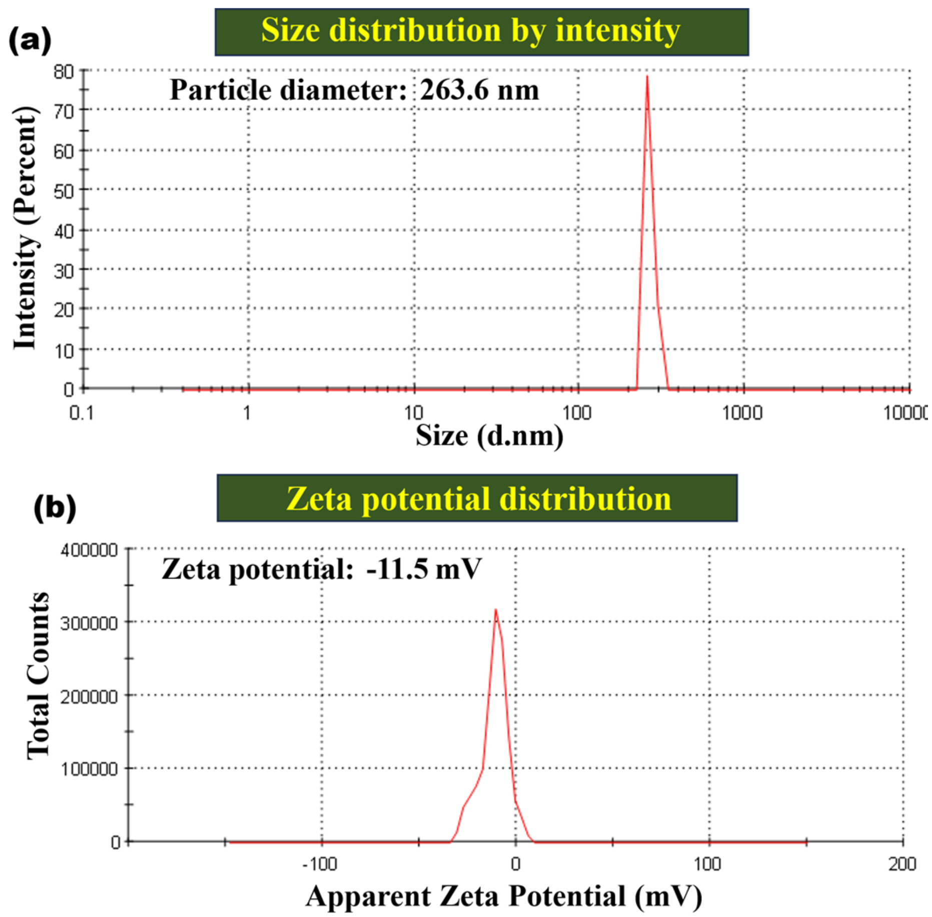

Fig. S3. (a) Particle size, (b) Zeta potential of NN-ZnO

Electrochemical impedance spectroscopy (EIS) analysis

Table S4 Summary of Electrochemical impedance spectroscopy (EIS) analysis.

(a) For 20% NN-ZnO

Parameter	Value
R_1 (Ω)	8.321
R_2 (Ω)	8.528
CPE-T ($F \cdot s^{n-1}$)	2.06×10^{-3}
CPE-P (n)	0.647
W_1–R (Ω)	3.583
W_1–T ($s^{1/2}$)	2.82×10^{-4}
W_1–P	0.392

(b) For ZnO

Parameter	Value
R_1 (Ω)	10.34
R_2 (Ω)	13.81
CPE-T ($F \cdot s^{n-1}$)	2.84×10^{-3}
CPE-P (n)	0.687
W_1–R (Ω)	2.55
W_1–T ($s^{1/2}$)	8.69×10^{-4}
W_1–P	0.405

Photocatalytic Hydrogen generation

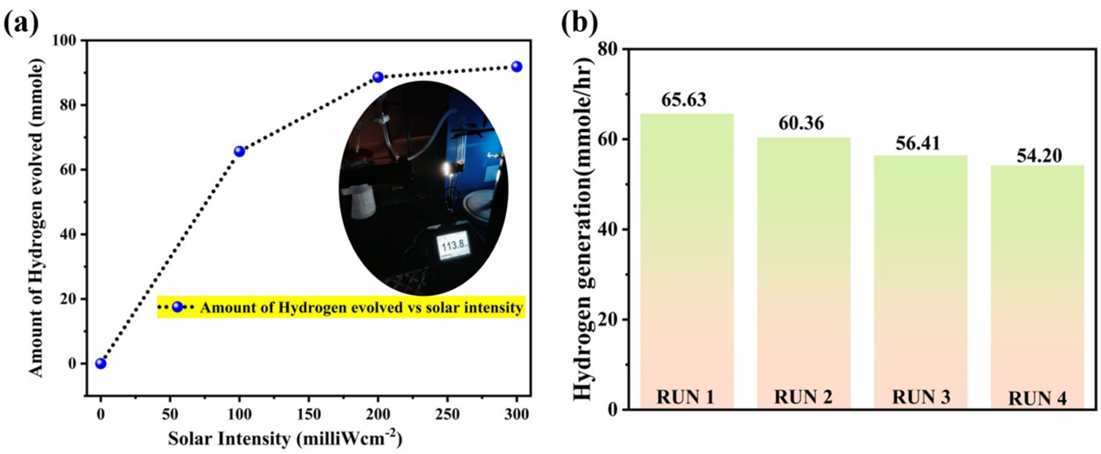

Fig. S4 (a) Variations of H_2 evolution over 6 hrs versus solar intensity, (b) Changes in H_2 evolution (mmole/hr) after 4 consecutive runs.

Table S5 Comparison of various aspects related to hydrogen generation using (NN+ZnO) mixture and NN-ZnO nanohybrid.

Aspect	Mixture (Biomass + ZnO + Water + Ethanol)	Nanohybrid (Biomass–ZnO Composite)
State of biomass	Raw organic polymers (cellulose, lignin, etc.)	Biomass (carbonaceous, aromatic, conductive)
Role of biomass	Hole scavenger (sacrificial donor); Supports ZnO particles physically	Co-catalyst; Conductive electron mediator; Visible-light absorber
Bonding with ZnO	Weak physical adsorption / chelation	Strong anchoring, Zn–O–C linkages
Electron transport	Very poor (insulating)	Excellent (conductive carbon network)
Light absorption	Mainly UV (from ZnO only)	UV + visible (biomass broadens absorption)
Charge separation	Low (fast recombination of e^--h^+)	High (biomass extracts and stores e^-)
Surface area or porosity	Moderate (raw biomass)	High (biomass has porous structure)
Hydrogen generation	Low as driven only by ZnO, aided by ethanol or biomass hole scavenging	High as synergistic ZnO–biomass heterojunction drives strong H_2 evolution
Main reactions	ZnO photoexcites → e^- + h^+; biomass or ethanol consume h^+; water provides H^+ → H_2	ZnO photoexcites e^- transfer to biomass e^- reduce H^+ → H_2 h^+ oxidize water

S3. Estimation of cost for Nelumbo Nucifera biomass with ZnO

Basis: 0.5 gm photocatalyst, 1 day/24 hrs operation (4 cycles of each 6 hrs operations considering recyclability of the catalysts). The cost is normalized with the production rate ($mmole/gm_{cat}day$) in order to assess the cost effectiveness and benefits.

Table S6 Solar H_2 generation by pristine ZnO photocatalyst (base case):

	Chemicals	Approx. quantity	Cost ($)
Chemicals	Zinc oxide	0.5 gm	0.0015
	Deionized water	50 ml	00.00
	Ethanol	20 ml	0.0144
Electricity involved	Stirring	4 hrs (2.2 KWh)	0.264
	Hydrothermal/ calcination	6 hrs (9 KWh)	1.08
	Drying	2 hrs (4 KWh)	0.48
H_2 generation performance in presence of solar simulator			
Chemicals	Sodium sulfide	1 ml	0.00087
Electricity involved	Ultra- sonication	0.5 hr (0.05 KWh)	0.006
	Solar simulator	24 hrs (2.4 KWh) (4 cycles)	0.288
Total			2.1348
Amount of H_2 evolution in 4 cycles (refer recyclability table)			72.32 mmole (1day)
Normalized cost per photocatalytic activity		$Total\ cost/mmole\ gm_{cat}{}^{-1}$	$0.0295 $/mmole\ gm_{cat}{}^{-1}\ day^{-1}$

Table S7 Solar H_2 generation by NN-ZnO photocatalyst

The cost estimated of NN-ZnO photocatalyst to H_2 generation are depicted below:

	Chemicals	Approx. quantity	Cost ($)
Pre-processing of NN stems			
Floral waste	Waste (NN stems)	1 kg (approx.)	Waste
Electricity involved	Freeze drying (vacuum pump, refrigeration etc.)	12 hrs (10 KWh)	1.2
	Drying	12 hrs (14.4 KWh)	1.728
Total amount of NN biomass powder extracted (from 1 kg)		25 gm	2.928
Synthesis of NN-ZnO			
Chemicals	Fine NN powder	0.1 gm	0.0117
	Deionized water	50 ml	00.00
	Zinc oxide	0.5 gm	0.0015
	Ethanol	20 ml	0.0144
	Sodium hydroxide	8 gm	0.11
Electricity involved	Stirring	6 hrs (3.3 KWh)	0.396
	Hydrothermal/ calcination	14 hrs (21 KWh)	2.52
	Drying	1 hr (2 KWh)	0.24
H_2 generation performance in presence of solar simulator			
Chemicals	Sodium sulfide	1 ml	0.00087
Electricity involved	Ultra-sonication	0.5 hr (0.05 KWh)	0.006
	Solar simulator	24 hrs (2.4 KWh) (4 cycles)	0.288
Total			3.5885
Amount of H_2 evolution in 4 cycles (refer recyclability table)			236.6 mmole (1day)
Normalized cost per photocatalytic activity		$Total\ cost/mmole\ gm_{cat}{}^{-1}\ da$	$0.01516 $/mmole\ gm_{cat}{}^{-1}\ day^{-1}$