

Review of CO₂ reduction photocatalysts with a sustainability perspective

Supplementary Information

*Pınar Özdemir^a, Beyza Yılmaz^a, and Ramazan Yıldırım**

Department of Chemical Engineering, Boğaziçi University, 34342, Bebek-Istanbul,
Turkey

*Corresponding author email: yildirra@boun.edu.tr

S1. Color Codes and Categorization Methodology

Table S1 was created based on five categorical levels. Even if descriptions of these levels can change according to column topic, they have same metrics tendency. If positive metrics are represented by green scale and risk metrics are colored by reversed scale.

Here is the general color scale applied on all columns of tables for major semiconductors and co-catalysts assessment.

Table S1. Color legend for categorization of semiconductors and co-catalysts.

Color	Level	Meaning
■ Dark green	Very low	Sustainable / Low risk
■ Light green	Low	Positive
■ Yellow	Moderate	Moderate
■ Orange	High	Increasing risk
■ Red	Very high	Critical / Negative/ Low stability

In addition to color codes of Table S1, each column of Table S11 and S21 was scaled by a simple criterionization based on their topic. These were clarified below step by step for each table.

S2. Clarification for Table of Major Semiconductors Assessment

S2.1. Abundance

Abundance column was totally scaled and filled based on information of EU critical raw material report¹. Elemental composition and global supply/production level were taken into consideration, and a logical scale was defined as given in Table S2.

Table S2. Colored logic scale for abundance column.

Color	Level	Meaning
■ Dark green	Very high	Abundant and common element base like metal-free or oxide minerals
■ Light green	High	Non-critical metal but not unlimited like Zn, S
■ Yellow	Moderate	Limited access by regulation/byproduct production like Pb-containing perovskite or systems dependent on CRMs
■ Orange	Low	Materials are non-toxic but consist of CRMs
■ Red	Very low	Toxic and CRMs

S2.2. Industrial maturity

Industrial maturity column was compiled from the literature survey. The starting point of the logical scale has been defined based on whether it is industrial production or laboratory scale (as shown in Table S3).

Table S3. Colored logic scale for industrial maturity.

Color	Level	Meaning
-------	-------	---------

■ Dark green	Very high	Bulk chemical industry
■ Light green	High	Industrial precursor + scalable oxide
■ Yellow	Moderate	Semi-industrial synthesis
■ Orange	Low	Still evolving
■ Red	Very low	Unique or rare production routes

S2.3. Process complexity

Process complexity column was filled according to production methods/steps, if there is multi-step, redox control or heterostructure. The complexity of synthesis routes was scaled and defined as shown in Table S4.

Table S4. Colored logic scale for process complexity.

Color	Level	Meaning
■ Dark green	Very low	Direct utilization
■ Light green	Low	Single step or calcination
■ Yellow	Moderate	Morphology tuning
■ Orange	High	Oxidation-state control or aggressive chemistry
■ Red	Very high	Multiple step + modifications

S2.4. Supply risk (from EU critical raw material report)

EU critical raw materials report gave a threshold value for supply risk ($SR \geq 1.0$)¹. If SR values of a material are equal or higher than 1.0, it is accepted critical in terms of supply risk. In the light of threshold value of EU report, SR column was filled according to SR value of each semiconductor or components. The supply risk of semiconductors was scaled and defined as shown in Table S5.

Table S5. Colored logic scale for supply risk.

Color	Level	Meaning
■ Dark green	Very low	EU non-critical ones like g-C ₃ N ₄ metal-free or Ti, Zn
■ Light green	Low	EU non-critical and produced ones from abundant components like r-GO and GO
■ Yellow	Moderate	EU non-critical but strategic/demanded ones like Cu
■ Orange	High	EU critical and regulatory restricted ones like Cd, Pb
■ Red	Very high	EU critical and non-environmentally ones

S2.5. Energy intensity

Energy intensity column was filled according to energy requirements of synthesis routes such as calcination/reduction temperature or hotspots of LCA. The energy intensity of synthesis routes was scaled and defined as shown in Table S6.

Table S6. Colored logic scale for energy intensity.

Color	Level	Meaning
■ Dark green	Very low	Direct utilization or single step
■ Light green	Low	single step + calcination

■ Yellow	Moderate	morphology tuning/drying/thermal treatment but limited energy input
■ Orange	High	oxidation-state control/high temperature/long duration/multiple post-treatment
■ Red	Very high	Aggressive and non-environmentally chemistry

S2.6. Water consumption

Water consumption column was scaled according to washing cycles, acidic oxidations, and solution synthesis of semiconductors. The water consumption of semiconductors was scaled and defined as shown in Table S7.

Table S7. Colored logic scale for water consumption.

Color	Level	Meaning
■ Dark green	Very low	Mostly dry synthesis
■ Light green	Low	Solvent-free or minimum washing cycles
■ Yellow	Moderate	Morphology tuning/drying/thermal treatment but limited energy input
■ Orange	High	Solvent-added synthesis + washing
■ Red	Very high	Intensive washing/purification or solvent separation chain

S2.7. Human/environmental toxicity

Human/environmental toxicity column was scaled according to environmental risk severity rather than intrinsic material toxicity. Human/environmental toxicity of semiconductors was scaled and defined as shown in Table S8.

Table S8. Colored logic scale for human/environmental toxicity.

Color	Level	Meaning
■ Dark green	Very low	Metal-free
■ Light green	Low	Inert oxides
■ Yellow	Moderate	Ion dissolution possible ones
■ Orange	High	Restricted toxicity
■ Red	Very high	Strongly toxic or hazardous chemistry

S2.8. CO₂ reduction performance

PCCO₂R performance column was scaled according to found maximum yields and visible-light capability of semiconductors. Here two highest yields are just selected: one for liquid and another for gaseous phase. If the products have just yield of just gas or liquid phases, the two highest yields from same phase were selected for each semiconductor. PCCO₂R performance of semiconductors was scaled and defined as shown in Table S9.

Table S9. Colored logic scale for PCCO₂R performance.

Color	Level	Meaning
■ Dark green	Very high	Highest yields + visible light-driven
■ Light green	High	Highest yields + UV light-driven
■ Yellow	Moderate	Modest yields among them + variable light irradiation

■ Orange	Low	Lower yields among them + variable light irradiation
■ Red	Very low	Lowest yields among them + UV light irradiation

S2.9. Overall sustainability

The overall stability column is a combination of abundance, industrial maturity, supply risk, energy intensity, toxicity, water consumption, and stability limitations for each semiconductor. Overall stability of semiconductors was scaled and defined as shown in Table S10.

Table S10. Colored logic scale for overall stability.

Color	Level	Meaning
■ Dark green	Very high	High performance + lowest toxicity
■ Light green	High	High performance + lowest toxicity but high energy input
■ Yellow	Moderate	Efficient but unstable/footprint issue/UV active
■ Orange	Low	Efficient but consist of critical raw material
■ Red	Very low	High toxicity (in)dependent of performance

Table S11. Assessment of major semiconductors used in the photocatalytic CO₂ reduction process

Material	Abundance	Industrial maturity	Process complexity	Supply risk (EU) ¹	Energy intensity (relative)	Water consumption	Human/environmental toxicity	PCCO ₂ R performance*	Overall sustainability
g-C ₃ N ₄	■ Very high - C, N ubiquitous	■ Moderate - thermal polymerization (urea, melamine) ²	■ Low - simple-batch calcination	■ Very low - EU non-critical	■ Moderate - 500-600 °C calcination hotpot ³	■ Low - mostly solvent-free ³	■ Very low - metal-free	■ High - Moderate - CO 883 ⁴ ; HCOOH 5069 ⁵ μmolg ⁻¹ cat.h ⁻¹	■ Very high - metal-free and low toxicity
TiO ₂	■ Very high - oxide minerals abundant	■ Very high - sulfate/chloride industry ⁶	■ Low - mature scalable	■ Very low - EU non-critical	■ High - industrial calcination ⁷	■ Moderate - wet processing ⁸	■ Low - inert oxide	■ High - CO 1223 ⁹ ; CH ₄ 1290 ¹⁰ μmolg ⁻¹ cat.h ⁻¹ (UV)	■ High - industrially robust but energy heavy
Cu ₂ O/CuO	■ Very high - Cu abundant	■ High - oxidation/precipitation ^{11,12}	■ High - multi-step redox control needed	■ Moderate - non-critical but strategic metal	■ High - post-treatment/calcination ¹³	■ Moderate - washing cycles ¹⁴	■ Moderate - Cu ⁺ /Cu ²⁺ ion release	■ High - CH ₃ OH 1.2 molg ⁻¹ cat.h ⁻¹¹⁵ ; CH ₄ 14.93 mmolg ⁻¹ cat.h ⁻¹¹⁶	■ Moderate - active but stability-limited
ZnO	■ High - Zn widely mined	■ High - precipitation/hydrothermal ¹⁷	■ Moderate - morphology control	■ Low - EU non-critical	■ Moderate - calcination/heating ¹⁸	■ Moderate - solution washing ¹⁹	■ Moderate - Zn ²⁺ ecotoxicity via dissolution	■ Very high - CH ₃ OH 6700 ²⁰ ; CO 3814 ²¹ μmolg ⁻¹ cat.h ⁻¹	■ Moderate - High - efficient yet unstable
r-GO/GO	■ High - graphite-derived	■ Low - oxidation/reduction ²² emerging scale-up	■ High - process-dependent (oxidation + reduction)	■ Low - Moderate - carbon based (no CRM)	■ High - oxidation/reduction steps, electricity ²³	■ Very High - Hummers washing water-intensive ²³	■ Low - Moderate - nanocarbon ecotox depends on form	■ Moderate - CO 760 ²⁴ ; HCOOH 1975 ²⁵ μmolg ⁻¹ cat.h ⁻¹ -interface-dependent	■ Moderate - process footprint dominant

CsPbBr₃	■ Moderate - Cs/Pb/Br available but Pb regulated	■ Moderate - Solution-based synthesis common (lab-dominant) ²⁶	■ High - solvent-intensive + separations	■ High - Pb: regulatory/criticality concern	■ High - hot-injection (120-180°C) or multi-step ²⁶	■ High - solvent use + purification ²⁷	■ Very high - Pb toxicity/potential Pb ²⁺ release	■ Moderate - CO 401.2 ²⁸ ; CH ₄ ²⁹ 230.6 μmolg ⁻¹ cat.h ⁻¹ (visible)	■ Very low - performance good, toxicity dominates
ZnS	■ High - Zn non-critical + S abundant by-product	■ High - Coprecipitation/hydrothermal established ³⁰	■ Moderate - washing/drying + optional calcination	■ Low - EU non-critical	■ Moderate - post-treatment energy hotspot ³⁰	■ Moderate - repeated washing ³¹	■ Moderate - possible Zn ²⁺ release; S oxidation products	■ Moderate - CO 2075.7 ³² ; CH ₄ 53.72 ³³ ; HCOOH 234 ³⁴ μmolg ⁻¹ cat.h ⁻¹ (mostly UV)	■ Moderate - safe supply, UV limitation + corrosion
CdS	■ Moderate - Cd not scarce but restricted	■ Moderate - lab-scale routes common ³⁵	■ High - tox-handling + washing + composites	■ High - EU: strict regulatory control	■ High - upstream Cd refining burdens + processing ³⁶	■ High - washing/centrifugation wastewater ³⁶	■ Very high - Cd ²⁺ release + bioaccumulation	■ Moderate - CO 2322.8 ³⁷ ; CH ₄ 18.53 ³⁸ μmolg ⁻¹ cat.h ⁻¹ (visible)	■ Very low - toxicity outweighs performance
BiVO₄	■ Moderate - Bi + V from mining/refining (CRM ^{**})	■ Moderate - common in lab; scale depends on Bi/V ³⁹	■ High - calcination + dopants/heterojunctions	■ High - Bi and V listed as critical (EU)	■ High - post-calcination energy ⁴⁰	■ High - synthesis + washing water use ⁴⁰	■ Moderate - metal release potential, pH-dependent	■ Low - CO 138.4 ⁴¹ ; CH ₄ 32.6 ⁴² ; CH ₃ OH 583.35 ⁴³ μmolg ⁻¹ cat.h ⁻¹ (often composite)	■ Low - CRM risk + processing burden
BiOX (Cl/Br/I)	■ Moderate - Bi critical; halides available	■ Moderate - hydro/solvothermal common ⁴⁴	■ Moderate - low-T synthesis but washing/drying	■ High - Bi is critical (EU)	■ Moderate - reaction low-T, drying energy matters ⁴⁵	■ High - synthesis + washing water use ⁴⁶	■ Low-Moderate - generally stable; risks more "Bi sourcing"	■ Very low - CO 144.5 ⁴⁷ ; CH ₄ 11.93 ⁴⁸ μmolg ⁻¹ cat.h ⁻¹	■ Low-Moderate - selective but Bi-supply constrained

* The two highest yields were represented for liquid and gaseous phases. If the products have just yield of just gas or liquid phases, the two highest yields from same phase were selected for each semiconductors.

** CRM: critical raw materials.

S3. Clarification for Table of Major Co-catalysts Assessment

S3.1. Abundance

Abundance column was totally scaled and filled based on information of EU critical raw material report¹. Elemental composition and global supply/production level were taken into consideration, and a logical scale was defined as given in Table S12.

Table S12. Colored logic scale for abundance column.

Color	Level	Meaning
■ Dark green	Very high	Abundant and common element base like Fe
■ Light green	High	Earth-abundant metals, large global supply
■ Yellow	Moderate	Precious but not extremely scarce
■ Orange	Low	Noble metals with limited reserves
■ Red	Very low	PGM and ultra-rare metals

S3.2. Industrial maturity

Industrial maturity column was compiled from the literature survey. The starting point of the logical scale has been defined based on whether it is industrial production or laboratory scale for co-catalyst deposition (as shown in Table S13).

Table S13. Colored logic scale for industrial maturity.

Color	Level	Meaning
■ Dark green	Very high	Bulk or established chemical industry
■ Light green	High	Industrial production + additional applications
■ Yellow	Moderate	Semi-industrial synthesis
■ Orange	Low	Still evolving
■ Red	Very low	Unique or rare production routes

S3.3. Process complexity

Process complexity column was filled according to production methods/steps, if there is multi-step, extra solvent or post-treatment. The complexity of synthesis routes was scaled and defined as shown in Table S14.

Table S14. Colored logic scale for process complexity.

Color	Level	Meaning
■ Dark green	Very low	Simple impregnation or doping
■ Light green	Low	Combination of two simple synthesizes
■ Yellow	Moderate	Reduction or calcination
■ Orange	High	Simple modification methods
■ Red	Very high	Molecular complexes or coordination chemistry

S3.4. Supply risk (from EU critical raw material report)

EU critical raw materials report gave a threshold value for supply risk ($SR \geq 1.0$)¹. If SR values of a material are equal or higher than 1.0, it is accepted critical in terms of supply risk. In the light of threshold value of EU report, SR column was filled according to SR value of each semiconductor or components. The supply risk of co-catalyst was scaled and defined as shown in Table S15.

Table S15. Colored logic scale for supply risk.

Color	Level	Meaning
■ Dark green	Very low	EU non-critical ones
■ Light green	Low	EU non-critical and produced ones from abundant components
■ Yellow	Moderate	EU non-critical but strategic/demanded ones
■ Orange	High	EU critical and regulatory restricted ones
■ Red	Very high	EU critical and non-environmentally ones

S3.5. Energy intensity

Energy intensity column was filled according to upstream mining or refining footprint of each co-catalyst. The energy intensity of synthesis routes was scaled and defined as shown in Table S16.

Table S16. Colored logic scale for energy intensity.

Color	Level	Meaning
■ Dark green	Very low	Abundant metals and no refining burden
■ Light green	Low	Low energy demand
■ Yellow	Moderate	Morphology tuning/drying/thermal treatment but limited energy input
■ Orange	High	Extraction/refining energy input
■ Red	Very high	High extraction/refining energy hotspot

S3.6. Water consumption

Water consumption column was scaled according to purifications, washing cycles and synthesis solvent of co-catalysts. The water consumption of co-catalyst application was scaled and defined as shown in Table S17.

Table S17. Colored logic scale for water consumption.

Color	Level	Meaning
■ Dark green	Very low	Simple or mostly dry synthesis
■ Light green	Low	Solvent-free or minimum washing cycles
■ Yellow	Moderate	Morphology tuning/drying/thermal treatment but limited energy input
■ Orange	High	Solvent-added synthesis + washing
■ Red	Very high	Intensive washing/purification or solvent separation chain

S3.7. Human/environmental toxicity

Human/environmental toxicity column was scaled according to behavior of nanomaterials, ion release and persistence. Human/environmental toxicity of co-catalysts was scaled and defined as shown in Table S18.

Table S18. Colored logic scale for human/environmental toxicity.

Color	Level	Meaning
■ Dark green	Very low	Metal-free
■ Light green	Low	Inert or benign oxides
■ Yellow	Moderate	Oxidation state changes
■ Orange	High	Ion release and toxicity concerns
■ Red	Very high	Strongly toxic or hazardous chemistry

S3.8. PCCO₂R performance

PCCO₂R performance column was scaled according to found maximum yields and visible-light capability of semiconductors. Here are just selected two highest yields: one for liquid and another for gaseous phase. If the products have just yield of just gas or liquid phases, the two highest yields from same phase were selected for each semiconductor. PCCO₂R performance of semiconductors was scaled and defined as shown in Table S19.

Table S19. Colored logic scale for PCCO₂R performance.

Color	Level	Meaning
■ Dark green	Very high	Highest yields + visible light-driven
■ Light green	High	Highest yields + UV light-driven
■ Yellow	Moderate	Modest yields among them + variable light irradiation
■ Orange	Low	Lower yields among them + variable light irradiation
■ Red	Very low	Lowest yields among them + UV light irradiation











S3.9. Overall sustainability

Overall stability column is a combination of abundance, industrial maturity, supply risk, energy intensity, toxicity, water consumption and stability limitation of each semiconductor. Overall stability of semiconductors was scaled and defined as shown in Table S20.

Table S20. Colored logic scale for overall stability.

Color	Level	Meaning
■ Dark green	Very high	High performance + lowest toxicity or non-critical
■ Light green	High	High performance + low toxicity but high energy input
■ Yellow	Moderate	Efficient but unstable/footprint issue or UV active
■ Orange	Low	Efficient/moderate but critical/strategical raw material
■ Red	Very low	High toxicity (in)dependent of performance

Table S21. Assessment of major co-catalysts used in the photocatalytic CO₂ reduction process

Material	Abundance	Industrial maturity	Process complexity	Supply risk (EU) ¹	Energy intensity (relative)	Water consumption	Human/environmental toxicity	PCCO ₂ R performance*	Overall sustainability
									
Cu	■ High - earth-abundant, large mining base	■ Very high - photodeposition and impregnation well-established ⁴⁹	■ Moderate - calcination and reduction steps may increase complexity	■ Low - EU non-critical, strategic	■ Moderate - thermal treatments dominate ⁵⁰	■ Low - mostly solvent-free ⁵⁰	■ Moderate - oxidation/dissolution under irradiation	■ High - CO 870 ⁵¹ ; CH ₃ OH 627.66 μmolg ⁻¹ cat.h ⁻¹⁵²	■ High - Moderate - abundant but oxidation-sensitive
Ag	■ Moderate - precious but accessible	■ Very high - mature nanoparticle synthesis ⁵³	■ Moderate - wet-chemical routes with stabilizers	■ Low - EU non-critical	■ High - mining and nanoparticle synthesis energy ⁵⁴	■ Moderate - purification water demand ⁵⁵	■ High - Ag ⁺ release and sulfidation pathways	■ High - Moderate - HCOOH 421 ⁵⁶ ; CH ₄ 113.84 ⁵⁷ μmolg ⁻¹ cat.h ⁻¹	■ Moderate - performance vs. nano-fate trade-off
Au	■ Low - scarce noble metal	■ Very high - established deposition chemistry ⁵⁸	■ Moderate - reductive immobilization and ligand control	■ Moderate - EU non-critical but strategic metal	■ Very high - upstream mining footprint ⁵⁹	■ Moderate - purification steps ⁵⁹	■ Moderate - chemically inert but persistent	■ Very high - CO 8982 ⁶⁰ ; CH ₃ OH 232 ²⁰ μmolg ⁻¹ cat.h ⁻¹	■ Low - Moderate - high efficiency, high resource cost
Pt	■ Very low - PGM** scarcity	■ Very high - industrial catalytic maturity ⁶¹	■ Moderate - chloroplatinate reduction & dispersion control	■ Very high - CRM***	■ Very high - extraction/refining energy hotspot ⁵⁹	■ Moderate - post-treatment washing ⁵⁹	■ Moderate - low toxicity but resource-intensive	■ Low - CH ₄ 83.6 ⁶² ; CH ₃ OH 17.85 ⁶³ μmolg ⁻¹ cat.h ⁻¹	■ Low - Moderate - efficient yet resource-heavy
Pd	■ Very low - PGM reserves limited	■ High - mature catalytic processing ⁶⁴	■ Moderate - organometallic precursor routes	■ Very high - CRM	■ Very high - mining and refining dominant impacts ⁶⁵	■ Moderate - purification stages ⁶⁵	■ High - persistence and possible leaching	■ Moderate - Low - CO 581.9 ⁶⁶ ; CH ₃ OH 3.17 ⁶⁷ μmolg ⁻¹ cat.h ⁻¹	■ Low - Moderate - activity vs. scarcity trade-off

Co	■ Moderate - limited geographic supply	■ High - industrial alloy/catalyst production ⁶⁸	■ Moderate - calcination and redox treatments	■ Very high - CRM	■ High - mining and refining impacts ⁶⁹	■ Moderate - aqueous processing ⁷⁰	■ Very high - toxicity and ecological concerns	■ High - CO 2075.7 ³² ; CH ₄ 20.63 ⁷¹ μmolg ⁻¹ cat.h ⁻¹	■ Low - Moderate - catalytic benefits vs. toxicity
Ni	■ High - widely available	■ Very high - mature scalable routes ⁷²	■ Very low - simple impregnation/doping	■ Moderate - strategic raw material	■ Moderate - mining energy demand ⁷²	■ Moderate - washing steps ⁷³	■ High Moderate - soluble Ni species risk	■ Moderate - Low CO 599 ⁷⁴ ; CH ₄ 29.65 ⁷⁵ μmolg ⁻¹ cat.h ⁻¹	■ High - Moderate - abundant kinetic modifier
Ru	■ Very low - rare PGM by-product	■ Moderate - limited large-scale deposition ⁷⁶	■ Moderate - dispersion and oxidation control needed	■ Very high - CRM	■ Very high - upstream energy ⁷⁷	■ Moderate - moderate lab processing ²⁰²	■ Moderate - oxidation-state shifts and aggregation	■ Low - CO 124.8 ⁷⁸ ; CH ₄ 19.8 ⁷⁸ μmolg ⁻¹ cat.h ⁻¹	■ Very low - scarce despite strong activity
Re	■ Very low - rarest metals	■ Moderate - molecular catalyst handling ⁷⁹	■ Very high - coordination chemistry and immobilization	■ Very high - strategic EU material	■ Very high - high resource intensity ⁸⁰	■ Moderate - solvent-intensive synthesis ⁸⁰	■ Moderate - soluble perrhenate formation	■ Low - CO 76.8 ⁸¹ ; μmolg ⁻¹ cat.h ⁻¹ (often composite)	■ Very low - scarcity dominates sustainability
Fe	■ Very high - earth-abundant	■ Very high - mature industrial processing ⁸²	■ Very low - simple wet-chemical synthesis	■ Very low - EU non-critical	■ Moderate - low energy demand ⁸³	■ Low - minimal washing burden ⁸⁴	■ Low - benign oxide forms	■ Low - CO 122 ⁸⁵ ; CH ₄ 30 ⁸⁶ μmolg ⁻¹ cat.h ⁻¹	■ High - Moderate - low footprint alternative

* The two highest yields were represented for liquid and gaseous phases. If the products have just yield of just gas or liquid phases, the two highest yields from same phase were selected for each semiconductor.

**PGM: platinum group metal

***CRM: critical raw material

References

- 1 M. Grohol, V. Constanze, GROW DG and European Commision, *Study on the Critical Raw Materials for the EU*, 2023.
- 2 J. Tang, C. Guo, T. Wang, X. Cheng, L. Huo, X. Zhang, C. Huang, Z. Major and Y. Xu, *Carbon Neutralization*, 2024, **3**, 557–583.
- 3 M. Li, L. Yang, Y. Song, H. Hou, Y. Fang, Y. Liu, L. Xie and D. Lu, *Inorganics*, 2025, **13**, 300.
- 4 L. Li, D. Ma, Q. Xu and S. Huang, *Chem. Eng. J.*, 2022, **437**, 135153.
- 5 D. O. Adekoya, M. Tahir and N. A. S. Amin, *J. CO2 Util.*, 2017, **18**, 261–274.
- 6 Y. Dai, H. Dong, L. Sun, J. Li, T. Zhang, Y. Geng and Z. Liu, *Environ. Impact Assess. Rev.*, 2024, **105**, 107412.
- 7 M. del P. Rodríguez-Rojas, V. Bustos-Terrones, M. Y. Díaz-Cárdenas, E. Vázquez-Vélez and H. Martínez, *Sustainability*, 2024, **16**, 7751.
- 8 A. A. Keller, S. McFerran, A. Lazareva and S. Suh, *J. Nanoparticle Res.*, 2013, **15**, 1692.
- 9 J. Y. Do, V. Tamilavan, R. Agneeswari, M. H. Hyun and M. Kang, *J. Photochem. Photobiol. A Chem.*, 2016, **330**, 30–36.
- 10 M. Tahir, *Appl. Catal. B Environ.*, 2017, **219**, 329–343.
- 11 Y. Li, X. Zhang, H. Chen and Y. Li, *Catal. Commun.*, 2015, **66**, 1–5.
- 12 Y. Qu, X. Li, G. Chen, H. Zhang and Y. Chen, *Mater. Lett.*, 2008, **62**, 886–888.
- 13 S. Ali, A. Razzaq, H. Kim and S. Il In, *Chem. Eng. J.*, 2022, **429**, 131579.
- 14 S. Naz, A. Gul and M. Zia, *IET Nanobiotechnology*, 2020, **14**, 1–13.
- 15 Y. A. Wu, I. McNulty, C. Liu, K. C. Lau, Q. Liu, A. P. Paulikas, C.-J. Sun, Z. Cai, J. R. Guest, Y. Ren, V. Stamenkovic, L. A. Curtiss, Y. Liu and T. Rajh, *Nat. Energy*, 2019, **4**, 957–968.
- 16 D. Mateo, J. Albero and H. García, *Energy Environ. Sci.*, 2017, **10**, 2392–2400.
- 17 M. Izzi, M. C. Sportelli, L. Torsi, R. A. Picca and N. Cioffi, *ACS Appl. Nano Mater.*, 2023, **6**, 10881–10902.
- 18 *Int. Students Sci. Congr.*
- 19 B. S. Ramadan, Y. G. Wibowo, D. Anwar and A. T. Maryani, *Glob. NEST J.*, 2024, **26**, 1–18.
- 20 M. Izadpanah Ostad, M. Niknam Shahrak and F. Galli, *J. CO2 Util.*, 2021, **43**, 101373.

- 21 X. Liu, L. Ye, S. Liu, Y. Li and X. Ji, *Sci. Rep.*, 2016, **6**, 38474.
- 22 V. Agarwal and P. B. Zetterlund, *Chem. Eng. J.*, 2021, **405**, 127018.
- 23 V. Tzatzadakis, E. Giannakaki, F. Krasanakis, A. Skouras, A. G. Asimakopoulou, E. Patelarou, K. Chrissopoulou, S. H. Anastasiadis and M. M. Stylianakis, *ACS Omega*, 2026, **11**, 3108–3114.
- 24 Y. Rambabu, U. Kumar, N. Singhal, M. Kaushal, M. Jaiswal, S. L. Jain and S. C. Roy, *Appl. Surf. Sci.*, 2019, **485**, 48–55.
- 25 L. F. Garay-Rodríguez, E. Luévano-Hipólito and L. M. Torres-Martínez, *Mater. Sci. Semicond. Process.*, 2023, **161**, 107458.
- 26 Q. Chen, X. Lan, C. Ren, B. Qi and J. Shi, *J. Alloys Compd.*, 2022, **899**, 163316.
- 27 C. Hiragond, N. Powar and S.-I. In, *Nanomaterials*, 2020, **10**, 2569.
- 28 Z. Chen, Y. Hu, J. Wang, Q. Shen, Y. Zhang, C. Ding, Y. Bai, G. Jiang, Z. Li and N. Gaponik, *Chem. Mater.*, 2020, **32**, 1517–1525.
- 29 R. Das, A. Patra, S. K. Dutta, S. Shyamal and N. Pradhan, *J. Am. Chem. Soc.*, 2022, **144**, 18629–18641.
- 30 Y. Meng, G. Liu, G. Zuo, X. Meng, T. Wang and J. Ye, *Nanoscale*, 2022, **14**, 14455–14465.
- 31 M. M. Khan and K. O. Abdulwahab, *Mater. Sci. Semicond. Process.*, 2024, **181**, 108634.
- 32 J. Liu, M. Liu, S. Zheng, X. Liu, S. Yao, F. Jing and G. Chen, *J. Colloid Interface Sci.*, 2023, **635**, 284–294.
- 33 J. Xue, Z. Wang, Q. Jiang, H. Zhang, H. Guo, P. Liu, A. Zhang, J. Guo and J. Lu, *Mater. Today Chem.*, 2025, **49**, 103064.
- 34 A. R. A. Astuti, W. H. Saputera, D. Ariono, I. G. Wenten and D. Sasongko, *ACS Omega*, 2025, **10**, 5563–5573.
- 35 N. H. S. Suhaimi, J. A. Shah Syed, R. Azhar, N. S. Adzis, O. M. Abdul Halim, Y. H. R. Chang, S. H. Taylor, L. A. Bailey, M. H. Ab Rahim, M. Z. Ramli, W. I. Nawawi and M. A. Mohd Ishak, *Int. J. Hydrogen Energy*, 2025, **165**, 150929.
- 36 A. da Rocha, N. Menguy, C. Yéprémian, A. Couté and R. Brayner, *Nanomaterials*, 2020, **10**, 227.
- 37 R. Xiong, F. Liu, X. Xiao, Y. Xiao, B. Cheng and S. Lei, *Chem. Eng. J.*, 2025, **520**, 166224.
- 38 Afifa, K. Arshad, N. Hussain, M. H. Ashraf and M. Z. Saleem, *Mol. Catal.*, 2025, **576**, 114930.

- 39 M. Ganeshbabu, N. Kannan, P. S. Venkatesh, G. Paulraj, K. Jeganathan and D. MubarakAli, *RSC Adv.*, 2020, **10**, 18315–18322.
- 40 S. H. Chen, Y. S. Jiang and H. Y. Lin, *ACS Omega*, 2020, **5**, 8927–8933.
- 41 Y. Liu, C. Xing, Z. Yao, Q. Deng, T. Liang, S. Zhang, J. Pan, Z. Yu, T. Xie, R. Li and Y. Hou, *J. Colloid Interface Sci.*, 2025, **677**, 1095–1106.
- 42 Y. Wu, Y. Li, K. Zhang, J. Hu and H. Yan, 2025, **51**, 2071–2088.
- 43 P. Chang, H. Yu, Y. Zhang, Y. Gao, L. Zheng, K. Li, Y. Du, L. Wu and J. Liu, *J. Mol. Struct.*, 2025, **1324**, 140914.
- 44 M. Xiao, J. Kong, W. Wang, B. Yang and S. Q. Guo, *J. Alloys Compd.*, 2025, **1046**, 184670.
- 45 R. O. Gembo, R. Ratshiedana, L. M. Madikizela, I. Kamika, C. K. King'onde, A. T. Kuvarega and T. A. M. Msagati, *Catal. Sci. Technol.*, 2024, **14**, 6466–6495.
- 46 Y. Zhang, P. Zhang, Y. Lan, L. Zhang, J. Yan and X. Su, *Chem. Commun.*, 2026, 2877–2895.
- 47 J. Xie, X. Zhang, Z. Lu, J. Hu, A. Hao, Y. Feng and Y. Cao, *Inorg. Chem. Front.*, 2023, **10**, 5127–5135.
- 48 J. Sun, Y. Zhang, S. Fan, X. Li and Q. Zhao, *Appl. Catal. B Environ. Energy*, 2024, **356**, 124248.
- 49 N. Karimah, R. C. Andiani, W. P. Utomo, A. I. Rozafia, N. Farida, A. Rosyidah, R. Liu, Q. Xu and D. Hartanto, *South African J. Chem. Eng.*, 2025, **54**, 582–596.
- 50 J. Zia, S. Radhakrishnan, M. S. S. R. Tejaswini and U. Riaz, *Sustain. Energy Fuels*, , DOI:10.1039/D5SE01290B.
- 51 H. Yin and J. Li, *Appl. Catal. B Environ.*, 2023, **320**, 121927.
- 52 K. Wang, M. Cheng, F. Xia, N. Cao, F. Zhang, W. Ni, X. Yue, K. Yan, Y. He, Y. Shi, W. Dai and P. Xie, *Small*, 2023, **19**, 2207581.
- 53 L. Pourzahedi and M. J. Eckelman, *Environ. Sci. Nano*, 2015, **2**, 361–369.
- 54 M. Slotte and R. Zevenhoven, *J. Clean. Prod.*, 2017, **148**, 948–957.
- 55 Z. Han, H. Y. Teah, I. Hirasawa and Y. Kikuchi, *J. Clean. Prod.*, 2025, **494**, 145012.
- 56 X. Hao, J. Wu, X. Cai, K. Li, C. Song and X. Guo, *Appl. Catal. B Environ. Energy*, 2025, **373**, 125366.
- 57 Y. Ren and W. Li, *Mol. Catal.*, 2024, **562**, 114187.
- 58 X. Chen, C. Li, M. Grätzel, R. Kostecki and S. S. Mao, *Chem. Soc. Rev.*, 2012,

- 41, 7909.
- 59 P. Nuss and M. J. Eckelman, *PLoS One*, 2014, **9**, e101298.
- 60 B. Tahir, M. Tahir and N. S. Amin, *Appl. Surf. Sci.*, 2015, **338**, 1–14.
- 61 A. E. Hughes, N. Haque, S. A. Northey and S. Giddey, *Resources*, 2021, **10**, 93.
- 62 M. Ahmadi, S. M. Alavi and A. Larimi, *Inorg. Chem.*, 2023, **62**, 20372–20389.
- 63 D. Permporn, R. Khunphonoi, J. Wilamat, P. Khemthong, P. Chirawatkul, T. Butburee, W. Sangkhun, K. Wantala, N. Grisdanurak, J. Santatiwongchai, P. Hirunsit, W. Klysubun and M. D. G. de Luna, *Nanomaterials*, 2022, **12**, 474.
- 64 W. Gu, Y. Geng, S. Xiao, Z. Gao and W. Wei, *Sci. Total Environ.*, 2023, **904**, 167248.
- 65 International Platinum Group Metals Association, *The Life Cycle Assessment of Platinum Group Metals: Reference year 2022*, 2025.
- 66 X. Wang, Z. Wang, Y. Bai, L. Tan, Y. Xu, X. Hao, J. Wang, A. H. Mahadi, Y. Zhao, L. Zheng and Y.-F. Song, *J. Energy Chem.*, 2020, **46**, 1–7.
- 67 S. Cao, Y. Li, B. Zhu, M. Jaroniec and J. Yu, *J. Catal.*, 2017, **349**, 208–217.
- 68 Q. Zhu, T. Nan, X. Fan, S. Peng, J. Liu, S. Tang and J. Yang, *J. Environ. Chem. Eng.*, 2026, **14**, 121398.
- 69 R. Aromaa-Stubb, M. Rinne and M. Lundström, *J. Sustain. Metall.*, 2024, **10**, 1795–1806.
- 70 K. Bang, J. Jung, Y. Han and H. Song, *Bull. Korean Chem. Soc.*, 2025, **46**, 1028–1047.
- 71 R. Xiong, X. Ding, Y. Sun, F. Liu, Y. Xiao, B. Cheng and S. Lei, *Sep. Purif. Technol.*, 2025, **358**, 130469.
- 72 M. Mistry, J. Gediga and S. Boonzaier, *Int. J. Life Cycle Assess.*, 2016, **21**, 1559–1572.
- 73 N. Zahir, V. Rajangam, S. S. Kalanur, S. I. Nikitenko and B. G. Pollet, *Energy Environ. Mater.*, , DOI:10.1002/eem2.70014.
- 74 F. Wu, C. Zhou, Y. Tang, J. Han, W. Xing, G. Wu and Y. Huang, *Mol. Catal.*, 2025, **576**, 114940.
- 75 Z. Wang, F. Su, H. Cao, M. Tian, X. Li, H. Xie, X. Jin, Z. Li and X. Y. Kong, *Mol. Catal.*, 2024, **552**, 113685.
- 76 N. T. Nassar, D. Pineault, S. M. Allen, D. M. McCaffrey, A. J. Padilla, J. L. Brainard, M. Bayani, E. Shojaeddini, J. W. Ryter, S. Lincoln and E. Alonso, *Methodology and technical input for the 2025 U.S. List of Critical Minerals—*

Assessing the potential effects of mineral commodity supply chain disruptions on the U.S. economy, 2025, vol. 2025.

- 77 M. Cabrero-Antonino, B. Ferrer, H. G. Baldoví and S. Navalón, *Chem. Eng. J.*, 2022, **445**, 136426.
- 78 S. Ling, K. Tang, Y. Zheng, B. Su, X. Lin, X. F. Lu, Y. Hou, Z. Ding and S. Wang, *Trans. Tianjin Univ.* 2026, 2026, 1–10.
- 79 A. V. Müller, L. A. Faustino, K. T. De Oliveira, A. O. T. Patrocínio and A. S. Polo, *ACS Catal.*, 2023, **13**, 633–646.
- 80 K. Kamogawa, Y. Kato, Y. Tamaki, T. Noguchi, K. Nozaki, T. Nakagawa and O. Ishitani, *Chem. Sci.*, 2024, **15**, 2074–2088.
- 81 C. Shen, X. Meng, R. Zou, K. Sun, Q. Wu, Y. Pan and C. Liu, *Angew. Chemie Int. Ed.*, 2024, **63**, e202402369.
- 82 G. M. Olmez, F. B. Dilek, T. Karanfil and U. Yetis, *J. Clean. Prod.*, 2016, **130**, 195–201.
- 83 D. Wang, R. Huang, W. Liu, D. Sun and Z. Li, *ACS Catal.*, 2014, **4**, 4254–4260.
- 84 M. Khalil, J. Gunlazuardi, T. A. Ivandini and A. Umar, *Renew. Sustain. Energy Rev.*, 2019, **113**, 109246.
- 85 Y. N. Jing, X. L. Yin, L. L. Li, Y. L. Wang, J. Xue, Z. F. Xu, D. Q. Liu, C. W. Chen, X. J. Liu and E. K. Liu, *J. Colloid Interface Sci.*, 2024, **668**, 161–170.
- 86 Q. Lin, J. Zhao, P. Zhang, S. Wang, Y. Wang, Z. Zhang, N. Wen, Z. Ding, R. Yuan, X. Wang and J. Long, *Carbon Energy*, , DOI:10.1002/cey2.435.