Functions of CNMs in Photocatalytic H2 Generation

Subjects: Materials Science, Composites

Contributor: Muhammad Asghar Rasool , Rabia Sattar , Ayesha Anum , Sami A. Al-Hussain , Sajjad Ahmad , Ali Irfan , Magdi E. A. Zaki

To improve photocatalysis, scientists are turning to carbon-based nanomaterials (CNMs) such as graphene, carbon nanotubes (CNTs), graphitic carbon nitride (g-C_3N_4), fullerene (C_{60}), carbon dots (CDs), and carbon nanofibers (CNFs), etc. Carbon-based nanomaterials show exceptional physicochemical properties, including thermal and chemical stability, high surface area, and better electrical, mechanical, and optical properties. Green energy must replace fossil fuels, and hydrogen is a prime choice. Photocatalytic water splitting (PWS) under solar irradiation could address energy and environmental problems.

semiconductor photocatalysis water splitting carbon nanomaterials

1. Structural Support to Improve Structure Sustainability

In semiconductor photocatalysis, different carbon compounds such as CNTs, CDs, graphene, GO, and activated carbon (AC) serve as structural support [1][2][3][4][5]. Carbon nanomaterials offer a larger surface site for the dissemination and immobilization of nanoparticles (NPs). These inert and thermally stable CNMs maintain their structure and properties when coupled with NPs. Numerous defect and active sites (oxygen-based functional groups) present in carbon materials can be exploited to initiate the development and anchoring of homogenous nanoparticles. The carbon materials' light weight is essential for their use as structural support. It is now also possible to produce activated carbon, carbon fibers, CNTs, and graphene on a considerable scale and inexpensively due to the copious amount of carbon in the earth's crust. The presence of these carbon components can change nucleation and growth rates, slowing down semiconductor nanoparticle aggregation and strengthening their architectures [6][7][8]. This section discusses how carbon-based materials stabilize nanostructures. Thus, structural stability applies to component geometries and morphologies. Extremely small nanoparticles, clusters, or other nanostructures that are dispersed and stabilized can substantially increase structural strength. As a result, semiconductor nanoparticles possess a large surface area, numerous surface defects, and a superior contact interface with carbon materials for increased charge transfer. Therefore, carbon-based hybrid semiconductor photocatalysts are more effective at producing H_2 than pure semiconductor photocatalysts. The surface chemistry of carbon materials is greatly impacted by interactions between semiconductor nanoparticles and carbon material. Wang et al. [3] proposed that hydroxyl, carboxyl, carbonyl, and epoxy groups increased the hydrophilic property of the CNTs surface by first treating them with HCl and HNO_3. The $Zn_xCd_{1-x}S$ nanoparticles were then supported by the functionalized CNTs using a solvothermal technique with the help of the raw ingredients including zinc acetate, cadmium chloride, and thiourea. The well-organized $Zn_{0.83}Cd_{0.17}S$ nanoparticles on the CNTs surface have a diameter of about 100 nm. If CNTs were not there, these nanoparticles would stick together. The excellent dispersion improves the interfacial surface of the $Zn_{0.83}Cd_{0.17}S$/CNT photocatalyst. Since the conduction band of the photocatalytic material is more populated than the Fermi level of CNTs, photoexcited electrons will move to the surface of the nanotubes. Thus, the aforesaid phenomenon can efficiently separate photoinduced charge carriers at the photocatalyst's interface. In addition, CNT-incorporated $Zn_{0.83}Cd_{0.17}S$ nanocomposite has a lower band gap value than pure $Zn_{0.83}Cd_{0.17}S$. Under 300 to 800 nm illumination, $Zn_{0.83}Cd_{0.17}S$/CNT nanocomposite generates 6.03 $mmol·h^{-1}g^{-1}$ of H_2, which is 1.5 times more than the pristine $Zn_{0.83}Cd_{0.17}S$.

Li et al. [9] prepared CdS-coupled graphene nanosheets via a hydrothermal approach using GO as supporting material, Cadmium acetate for Cd^{2+} precursor, and DMSO as the solvent as well as source of S^{2-}. Solvothermal heating turned GO into graphene with CdS clusters on its surface. The interactions between nanoparticles and graphene can be strengthened by physical adsorption, the electrostatic force of attractions, and charge transference. The homogenous CdS cluster distribution on graphene, the CdS/graphene photocatalyst, has a greater specific surface area. Uniform CdS cluster distribution is attributed to the more effective transport of photoexcited charges to graphene. At 1.0 wt% graphene, 1.12 $mmol·h^{-1}$ of hydrogen is generated, which is 4.87 times than the neat CdS. Shen et al. [10] also used rGO additive to stabilize the very thin nanorods of $Zn_{0.5}Cd_{0.5}S$ with a corresponding upsurge in photocatalytic H_2 evolution.

2. Cocatalyst

Cocatalysts in a photocatalytic system enhance H_2 evaluation efficacy. Metals such as Pt, Au, or Pd have a more significant work function than semiconductors, making them excellent cocatalysts. Cocatalysts improve charge separation, provide catalytic sites, reduce over-potential, and minimize H_2 activation energy [11][12]. Noble metals are expensive and rare. Thus, economical cocatalysts are needed for economic photocatalytic systems. Carbon compounds are effective cocatalysts for photocatalytic H_2 evaluation [13][14]. The Fermi level of carbonaceous compounds is lesser than CB but RP is greater than H^+/H_2. Carbon compounds have advantages similar to noble metal cocatalysts, with increased active sites and a localized photothermal effect owing to increased surface area and extended light absorption intensity [15][16]. Khan et al. [13] fabricated a CNTs/CdS/TiO_2/Pt photocatalyst via the hydrothermal method. Pt was designed onto TiO_2 via photodeposition whilst CdS via hydrolysis. This photocatalyst generates H_2 at a greater rate under visible radiations, using sodium sulfide and sulfate sacrificial agents. In the first step, the electrons and holes are separated between the TiO_2 and CdS interface. The photoelectron moves from the TiO_2 to the CNT surface and then Pt catalyst. The Pt nanoparticles work as cocatalysts due to their lower Fermi level of CNTs as compared to TiO_2. Both Pt and CNTs are promising photocatalysts and can improve the photo-catalytic H_2 evaluation of CdS/TiO_2. Preferably, using 0.4 and 4 wt.% of Pt and CNTs, respectively, enhances the photocatalytic performance by 50%. A graphene/MoS_2/TiO_2(GMST) photocomposite was prepared hydrothermally using Na_2MoO_4, H_2NCSNH_2, and graphene oxide precursors at 210 °C and utilized as an efficient material for photocatalytic H_2 production [17]. It was exposed by using ethanol as a sacrificial agent and TiO_2 as the photocatalyst while graphene and MoS_2 functioned as cocatalysts. The GMST photocatalyst exhibited a high rate

(~165.3 mol·h^{-1}) of H_2generation at 5.0 and 0.5 wt.% of graphene and MoS_2, respectively, having 9.7% quantum efficiency (QE) at 365 nm [17]. A hybrid rGO/$Zn_xCd_{1-x}S$ photocatalyst prepared first via coprecipitation and then a hydrothermal reduction approach elevates the cocatalytic performance for H_2 production [18]. A high rate of H_2 evaluation (~1824 mol·h^{-1}g^{-1}) was observed for this optimized photocatalyst using 0.25 wt.% of rGO, which has 23.4% apparent QE at 420 nm under solar irradiation. Liu et al. integrated NH_3-treated CDs into g-C_3N_4 by heating CDs and urea for 3 h at 550 °C, where the carbon dots were first synthesized electrochemically and then hydrothermally treated with ammonia. This g-C_3N_4/CDs hybrid photocatalyst was found to be efficient in WS under solar light for the evolution of H_2 and O_2. A maximum QE of 16% was achieved using a g-C_3N_4/CD catalyst at 420 ± 20 nm. Actually, the photocatalytic action of g-C_3N_4 at the first stage caused water to be split into H_2O_2 and H_2, then, at the subsequent stage, the carbon dot-catalyzed breakdown of H_2O_2 into H_2O and O_2.

3. Photosensitization

Carbon compounds with semiconducting or dye-like characteristics can function as a photosensitizer in some cases, enhancing the photoresponse of a broad bandgap of the semiconductor photocatalyst by inducing additional photogenerated electrons [19][20][21]. The emission of photoelectrons from the material can overlap with semiconductor absorption and are responsible for the transfer of the resonance energy from the carbon material to the coupled semiconductor. As the result, the LUMO of the carbon material becomes more negative in comparison to the coupled semiconductor's CB. Wang et al. [22] prepared a graphene/ZnS (G-ZS) photocatalyst via the hydrothermal method for photocatalytic H_2 evolution under visible light. A graphene-supported ZnS photocatalyst evaluated 7.42 mol·h^{-1}g^{-1} hydrogen at 0.1 wt.% graphene, which was found to be 8 times that of the pristine ZnS. Since visible light cannot excite ZnS, the photoelectron most likely originates from graphene and migrates to the CB of ZnS [19]. The rGO/Pt/TiO_2 photocatalyst is an excellent photosensitizer and evaluates H_2 at a rate of 11.24 mmol·h^{-1}g^{-1}. Carbon dots are excellent candidates for use as photosensitizers in photocatalytic reactions due to their high photo-absorption and photoluminescence properties. For instance, Martindale et al. [23] fabricated a carbon dot (photosensitizer)-based Ni-bis- (diphosphine) (NiP) photocatalyst for H_2 generation under visible light. To produce this photocatalyst, 30 nmol of NiP and 2.2 nmol of CD are used in 0.1M EDTA solution with pH 6; a photocatalyst g-CQDs/NiP produces H_2 at 398 mol·h^{-1}g^{-1}. The apparent QE at 360 ± 10 nm was observed ∼1.4%. Carbon dots can convert near-infrared photons for semiconductor photocatalysis due to their photoluminescence up-conversion property [21][24]. Hydrogenated TiO_2(H-TiO_2)-based photocatalysts were prepared with carbon quantum dots (CQDs) under bath reflux. This photocatalyst is UV-visible-NIR compatible and showed remarkable photocatalytic H_2 production capability under the illumination of a 300 W Xe arc lamp. For this photocatalytic system, Pt was used as the cocatalyst and methanol as the sacrificial agent across a wide spectral range. The higher H_2 generation rate of 7.42 mmol·h^{-1}g^{-1} was observed in comparison to H-TiO_2 nanobelts (6.01 mmol·h^{-1}g^{-1}) [24].

4. Photocatalyst

Carbon-based nanomaterials are effective photocatalysts for H_2generation, according to theory and experiment [25][26][27], owing to the semiconducting properties of CDs, CNTs, graphene, GO, rGO, and C_{60}. Such a nanocarbon of the semiconductor sort can have a greater number of negatively charged LUMO sites than H^+/H_2 RP. Reduced graphene oxide rGO is a commonly used photocatalyst [28][29], as its CB minimum consists of anti-bonding π* orbital; at pH = 0, it has a potential of −0.52 eV [30]. Density functional theory (DFT) studies explain the electronic structure of graphene oxide by alternating the relative ratio of -OH and epoxy groups present on the surface. The resulting electronic structure shows the photocatalytic hydrogen, and oxygen evaluation reaction occurs [31]. Teng's group reported that GO synthesized by a modified Hummers' method had an apparent direct E_g value of 3.3–4.3 eV and an indirect E_g of 2.4–3.0 eV. Graphene oxide (GO) is comprised of graphene molecules of different oxidation stats and can produce H_2 under UV/Visible illuminations. In a 20% methanol aqueous solution with 0.5g GO and no cocatalyst, mercury lamp irradiation yielded 17,000 $mmol{\cdot}h^{-1}$ H_2 [27]. Meng et al. [29] prepared a p-MoS_2/n-rGO photocatalyst with p-type MoS_2 deposited on the surface of n-type rGO. Under solar irradiation and ethanol as sacrificial agents, this photocatalyst exhibited higher H_2 evaluation activity than bare MoS_2 and MoS_2/rGO. This is because, as shown by the photoelectrochemical experiment, the p-MoS_2/n-rGO junctions are very good at separating charges. Zhu's team compared H_2 production activity for neat CDs and CD-based composite materials [26][32][33]. An H_2 evaluation at a 423.7 $mol{\cdot}h^{-1}g^{-1}$ was achieved using carbon dots in pure water without needing a cocatalyst. Carbon dots were created hydrothermally from MWCNTs oxide [26]. In methanol sacrificial agent and Pt cocatalyst, a hybrid carbon nanodot/WO_3 photocatalyst produces H_2 at 1330 $mol{\cdot}h^{-1}g^{-1}$ under xenon lamp irradiation [32].

5. Band Gap Narrowing Effect

Chemical bonds can form when semiconductor photocatalysts and carbon compounds make strong contacts (e.g., metal O C bonds). Chemical bonding reduces photocatalyst band gaps, increasing H_2 production [34][35]. Ye et al. [36] reported the hydrothermal fabrication of graphene/CdS (0.01:1) and CNTs/CdS (0.05:1) hybrid materials with the photocatalytic H_2 evaluation of and 52 $mol{\cdot}h^{-1}$, respectively. The addition of graphene or CNTs into CdS resulted in the narrowing of the E_g values of these hybrid photocatalysts and consequently led to superior photocatalytic H_2 generation as compared to pristine CdS. This was in addition to the benefit of more effective charge separation. Bi_2WO_6 is often not used for water-splitting H_2 generation, due to its smaller RP and comparatively less negative CB. However, coupling Bi_2WO_6 nanosheets with graphene, the CB of Bi_2WO_6 becomes more negative, and the feasibility of photocatalytic H_2 evaluation increases [37]. In a typical experiment [38], Bi_2WO_6 nanoparticles were produced via sonication onto the graphene's sheets using GO, HNO_3, $(NH_4)_{10}W_{12}O_{41}$, and $Bi(NO_3)_3{\cdot}5H_2O$, followed by calcination at 450°C for 3h in an inert environment. Raman and XPS research validated the chemistry between Bi_2WO_6 and graphene. After coupling with graphene, Mott–Schottky calculations showed that the RP of CB of Bi_2WO_6 increased from +0.09 V to −0.30 V as compared to the standard hydrogen electrode. As a result, 0.03 g of Bi_2WO_6/graphene photocatalyst was used to produce 159.2 $mol{\cdot}h^{-1}$ of H_2at 420 nm in an aqueous solution of methanol.

In conclusion, in several aspects, carbon materials can significantly enhance the H_2 reaction rate compared to semiconductor photocatalysts. The inclusion of various carbonaceous materials coupled with semiconductor photocatalysts can result in a variety of proficient effects including structural support for improved structure constancy, electron collection, the reduction of the recombination rate of photo-stimulated charge pairs, photocatalyst, E_g narrowing outcome cocatalyst, and photosensitization. It is essential to remember that certain carbon materials can potentially play many functions throughout the entire photocatalytic process. Moreover, due to some limitations imposed by its structure and properties, a particular type of carbon material might not be able to fulfill all the functions. The potential characteristics of various CNMs are summarized in **Table 1**.

Table 1. Role of carbon nanomaterials in photocatalysis.

Function Type	Carbon Nanotubes	Graphene	Fullerenes	Graphene Oxide	Graphitic Carbon Nitride	Carbon Quantum Dots
Supporting material	✔	✔	×	✔	✔	✔
Photocatalyst	✔	✔	✔	✔	×	✔
Cocatalyst	✔	✔	✔	✔	✔	✔
Photosensitizer	×	✔	✔	✔	✔	✔
Bandgap narrowing effect	✔	✔	×	✔	✔	✔

References

1. Chen, P.; Wang, L.; Wang, P.; Kostka, A.; Wark, M.; Muhler, M.; Beranek, R. CNT-TiO2−δ Composites for Improved Co-Catalyst Dispersion and Stabilized Photocatalytic Hydrogen Production. Catalysts 2015, 5, 270–285.
2. MamathaKumari, M.; Kumar, D.P.; Haridoss, P.; DurgaKumari, V.; Shankar, M. Nanohybrid of titania/carbon nanotubes-nanohorns: A promising photocatalyst for enhanced hydrogen production under solar irradiation. Int. J. Hydrog. Energy 2015, 40, 1665–1674.
3. Wang, L.; Yao, Z.; Jia, F.; Chen, B.; Jiang, Z. A facile synthesis of ZnxCd1−xS/CNTs nanocomposite photocatalyst for H2 production. Dalton Trans. 2013, 42, 9976–9981.
4. Kim, Y.K.; Kim, M.; Hwang, S.-H.; Lim, S.K.; Park, H.; Kim, S. CdS-loaded flexible carbon nanofiber mats as a platform for solar hydrogen production. Int. J. Hydrogen Energy 2015, 40, 136–145.
5. Kim, M.; Razzaq, A.; Kim, Y.K.; Kim, S.; In, S.-I. Synthesis and characterization of platinum modified TiO2-embedded carbon nanofibers for solar hydrogen generation. RSC Adv. 2014, 4,

51286–51293.

6. Wang, J.; Huang, H.; Xu, Z.; Kou, J.; Lu, C. The potential of carbon-based materials for photocatalytic application. Curr. Org. Chem. 2014, 18, 1346–1364.
7. Julkapli, N.M.; Bagheri, S. Graphene supported heterogeneous catalysts: An overview. Int. J. Hydrogen Energy 2015, 40, 948–979.
8. Li, Y.; Wang, H.; Peng, S. Tunable photodeposition of MoS2 onto a composite of reduced graphene oxide and CdS for synergic photocatalytic hydrogen generation. J. Phys. Chem. C 2014, 118, 19842–19848.
9. Li, Q.; Guo, B.; Yu, J.; Ran, J.; Zhang, B.; Yan, H.; Gong, J.R. Highly efficient visible-light-driven photocatalytic hydrogen production of CdS-cluster-decorated graphene nanosheets. J. Am. Chem. Soc. 2011, 133, 10878–10884.
10. Shen, S.; Ma, A.; Tang, Z.; Han, Z.; Wang, M.; Wang, Z.; Zhi, L.; Yang, J. Facile synthesis of Zn0.5Cd0.5S ultrathin nanorods on reduced graphene oxide for enhanced photocatalytic hydrogen evolution under visible light. ChemCatChem 2015, 7, 609–615.
11. Yang, J.; Wang, D.; Han, H.; Li, C. Roles of cocatalysts in photocatalysis and photoelectrocatalysis. Acc. Chem. Res. 2013, 46, 1900–1909.
12. Ran, J.; Zhang, J.; Yu, J.; Jaroniec, M.; Qiao, S.Z. Earth-abundant cocatalysts for semiconductor-based photocatalytic water splitting. Chem. Soc. Rev. 2014, 43, 7787–7812.
13. Khan, G.; Choi, S.K.; Kim, S.; Lim, S.K.; Jang, J.S.; Park, H. Carbon nanotubes as an auxiliary catalyst in heterojunction photocatalysis for solar hydrogen. Appl. Catal. B Environ. 2013, 142, 647–653.
14. Wen, J.; Li, X.; Li, H.; Ma, S.; He, K.; Xu, Y.; Fang, Y.; Liu, W.; Gao, Q. Enhanced visible-light H2 evolution of g-C3N4 photocatalysts via the synergetic effect of amorphous NiS and cheap metal-free carbon black nanoparticles as co-catalysts. Appl. Surf. Sci. 2015, 358, 204–212.
15. Gan, Z.; Wu, X.; Meng, M.; Zhu, X.; Yang, L.; Chu, P.K. Photothermal contribution to enhanced photocatalytic performance of graphene-based nanocomposites. ACS Nano 2014, 8, 9304–9310.
16. Sun, S.; Wang, W.; Jiang, D.; Zhang, L.; Zhou, J. Infrared light induced photoelectrocatalytic application via graphene oxide coated thermoelectric device. Appl. Catal. B Environ. 2014, 158, 136–139.
17. Xiang, Q.; Yu, J.; Jaroniec, M. Synergetic effect of MoS2 and graphene as cocatalysts for enhanced photocatalytic H2 production activity of TiO2 nanoparticles. J. Am. Chem. Soc. 2012, 134, 6575–6578.
18. Yu, J.; Yang, B.; Cheng, B. Noble-metal-free carbon nanotube-Cd0.1Zn0.9S composites for high visible-light photocatalytic H2-production performance. Nanoscale 2012, 4, 2670–2677.

19. Wang, P.; Dimitrijevic, N.M.; Chang, A.Y.; Schaller, R.D.; Liu, Y.; Rajh, T.; Rozhkova, E.A. Photoinduced electron transfer pathways in hydrogen-evolving reduced graphene oxide-boosted hybrid nano-bio catalyst. ACS Nano 2014, 8, 7995–8002.
20. Xie, S.; Su, H.; Wei, W.; Li, M.; Tong, Y.; Mao, Z. Remarkable photoelectrochemical performance of carbon dots sensitized TiO2 under visible light irradiation. J. Mater. Chem. A 2014, 2, 16365–16368.
21. Zhang, X.; Huang, H.; Liu, J.; Liu, Y.; Kang, Z. Carbon quantum dots serving as spectral converters through broadband upconversion of near-infrared photons for photoelectrochemical hydrogen generation. J. Mater. Chem. A 2013, 1, 11529–11533.
22. Wang, F.; Zheng, M.; Zhu, C.; Zhang, B.; Chen, W.; Ma, L.; Shen, W. Visible light photocatalytic H2-production activity of wide band gap ZnS nanoparticles based on the photosensitization of graphene. Nanotechnology 2015, 26, 345402.
23. Martindale, B.C.; Hutton, G.A.; Caputo, C.A.; Reisner, E. Solar hydrogen production using carbon quantum dots and a molecular nickel catalyst. J. Am. Chem. Soc. 2015, 137, 6018–6025.
24. Tian, J.; Leng, Y.; Zhao, Z.; Xia, Y.; Sang, Y.; Hao, P.; Zhan, J.; Li, M.; Liu, H. Carbon quantum dots/hydrogenated TiO2 nanobelt heterostructures and their broad spectrum photocatalytic properties under UV, visible, and near-infrared irradiation. Nano Energy 2015, 11, 419–427.
25. Dai, K.; Peng, T.; Ke, D.; Wei, B. Photocatalytic hydrogen generation using a nanocomposite of multi-walled carbon nanotubes and TiO2 nanoparticles under visible light irradiation. Nanotechnology 2009, 20, 125603.
26. Yang, P.; Zhao, J.; Wang, J.; Cui, H.; Li, L.; Zhu, Z. Pure carbon nanodots for excellent photocatalytic hydrogen generation. RSC Adv. 2015, 5, 21332–21335.
27. Yeh, T.F.; Syu, J.M.; Cheng, C.; Chang, T.H.; Teng, H. Graphite oxide as a photocatalyst for hydrogen production from water. Adv. Funct. Mater. 2010, 20, 2255–2262.
28. Xu, L.; Huang, W.-Q.; Wang, L.-L.; Tian, Z.-A.; Hu, W.; Ma, Y.; Wang, X.; Pan, A.; Huang, G.-F. Insights into enhanced visible-light photocatalytic hydrogen evolution of g-C3N4 and highly reduced graphene oxide composite: The role of oxygen. Chem. Mater. 2015, 27, 1612–1621.
29. Meng, F.; Li, J.; Cushing, S.K.; Zhi, M.; Wu, N. Solar hydrogen generation by nanoscale p–n junction of p-type molybdenum disulfide/n-type nitrogen-doped reduced graphene oxide. J. Am. Chem. Soc. 2013, 135, 10286–10289.
30. Xie, G.; Zhang, K.; Guo, B.; Liu, Q.; Fang, L.; Gong, J.R. Graphene-based materials for hydrogen generation from light-driven water splitting. Adv. Mater. 2013, 25, 3820–3839.
31. Jiang, X.; Nisar, J.; Pathak, B.; Zhao, J.; Ahuja, R. Graphene oxide as a chemically tunable 2-D material for visible-light photocatalyst applications. J. Catal. 2013, 299, 204–209.

32. Yang, P.; Zhao, J.; Wang, J.; Cao, B.; Li, L.; Zhu, Z. Construction of Z-scheme carbon nanodots/WO3 with highly enhanced photocatalytic hydrogen production. J. Mater. Chem. A 2015, 3, 8256–8259.
33. Yang, P.; Zhao, J.; Wang, J.; Cao, B.; Li, L.; Zhu, Z. Light-induced synthesis of photoluminescent carbon nanoparticles for Fe3+ sensing and photocatalytic hydrogen evolution. J. Mater. Chem. A 2015, 3, 136–138.
34. Yuan, Y.; Gong, X.; Wang, H. The synergistic mechanism of graphene and MoS2 for hydrogen generation: Insights from density functional theory. Phys. Chem. Chem. Phys. 2015, 17, 11375–11381.
35. Shaban, Y.A.; Khan, S.U. Visible light active carbon modified n-TiO2 for efficient hydrogen production by photoelectrochemical splitting of water. Int. J. Hydrogen Energy 2008, 33, 1118–1126.
36. Ye, A.; Fan, W.; Zhang, Q.; Deng, W.; Wang, Y. CdS-graphene and CdS-CNT nanocomposites as visible-light photocatalysts for hydrogen evolution and organic dye degradation. Catal. Sci. Technol. 2012, 2, 969–978.
37. Sun, Z.; Guo, J.; Zhu, S.; Ma, J.; Liao, Y.; Zhang, D. High photocatalytic performance by engineering Bi2WO6 nanoneedles onto graphene sheets. RSC Adv. 2014, 4, 27963–27970.
38. Sun, Z.; Guo, J.; Zhu, S.; Mao, L.; Ma, J.; Zhang, D. A high-performance Bi2WO6–graphene photocatalyst for visible light-induced H2 and O2 generation. Nanoscale 2014, 6, 2186–2193.

Retrieved from https://encyclopedia.pub/entry/history/show/91955