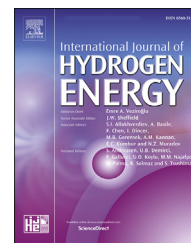


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A bibliometric examination and state-of-the-art overview of hydrogen generation from photoelectrochemical water splitting

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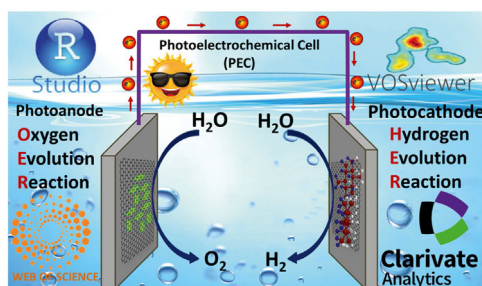
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HIGHLIGHTS

- A bibliometric analysis of photoelectrochemical and hydrogen production is conducted.
- Web of Science database from 1970 to 2022 was used in this review.
- The key findings from the article analysis are discussed.
- Future research potential and practical implications for the field of study are explored.

GRAPHICAL ABSTRACT



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ABSTRACT

Renewable energies can reduce emissions from fossil fuel-based power production by a significant amount, reducing climate change. Among the several options being investigated, hydrogen is now recognized as one of the primary enabling technologies for future large-scale and long-term green storage of renewable energy. However, using clean and renewable energy sources like water and sunlight is the best option. According to recent studies, photoelectrochemical (PEC) water splitting is a potential technology for creating hydrogen using free solar energy since hydrogen and oxygen gases may be easily identified in PEC. This study uses bibliometric and systematic literature review methodologies to examine the scientific understanding of PEC water splitting and hydrogen generation, evaluating 936 articles issued in the Web of Science database from 1970 to 2022. The authors looked at how PEC water splitting research has developed compared to prior research, what criteria make up practical approaches, and what subjects have emerged as new trends in reacting to changing situations. The key findings from the article analysis, future research potential, and practical implications for the field are discussed.

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Introduction

Fossil fuels will run out at some point, constitute a significant danger to environmental equilibrium, and are responsible for various ecological risks; thus, companies must transition to renewable energy sources as quickly as feasible. Acid rain and global warming are influenced by fossil fuel burning, which emits significant amounts of greenhouse and hazardous gases such as CO₂, SO₂, NO_x, and other pollutants. Therefore, renewable energy sources have become increasingly important as global warming and pollution have increased [1]. Furthermore, high-energy-density, sustainable, and scalable energy sources are urgently needed as alternatives to ensure energy supply and reduce the environmental effect of present non-renewable energy sources. Hydrogen is one of the most promising sustainable and clean energy bases since it produces just water as a byproduct and emits no carbon [2]. Hydrogen generated from renewable energy sources has the potential to be a clean, long-term energy carrier that can be made from domestic energy resources all around the world.

Hydrogen may be generated from diverse sources, including biomass, fossil fuels, and water electrolysis using electricity. Hydrogen generation from water is considered renewable energy because it employs the Earth's water cycle and gravitational force to make hydrogen. It also produces no greenhouse gas emissions or contaminants in the air. The environmental impact and energy efficiency of hydrogen depend on its production. However, using clean and renewable energy sources such as water and sunshine is preferable. Solar-powered hydrogen generation from water is a potentially practical approach to solving fuel production's environmental and global energy dilemmas [3]. Because of its promise as a clean energy source, the plentiful availability of sunlight has been the topic of significant research in the hunt for alternatives to non-renewable energy. According to recent studies, photoelectrochemical (PEC) water splitting is a viable

technique for hydrogen production using free solar energy since hydrogen and oxygen gases can be easily detected in PEC. The photoelectrode in the PEC technology collects sunlight and splits water into hydrogen and oxygen, potentially making hydrogen production more efficient and cost-effective [4]. The significant effort in PEC water splitting is still focused on improving the stability and effectiveness of the photoactive elements [5,6] to meet the needed efficiency objective of 10%, which is commercially practical [7].

Although several systematic studies have addressed the PEC field research status (Table 1), only two papers for the topic search of “photoelectrochemical” and “review” and title search of “systematic” have been detected in the WoS database [8,9]. Fig. 1 illustrates a word cloud of commonly used terms in photoelectrochemical and hydrogen literature. Although the word cloud contains the keywords of many authors, the figure demonstrates that, in addition to detecting common keywords, specific keywords seem to have a more substantial effect on the system (water, performance, visible light, etc.), and others have the least impact on the network. Upon utilizing search terms such as “systematic,” “photoelectrochemical,” and “review” in the title search, our investigation yielded no publication that has comprehensively reviewed the recent advancements in this subject matter through the lens of bibliometric analysis or presented the emerging trends in this research field, as highlighted in Table 1 and Fig. 1. As a result, this study will use an exhaustive assessment of Thomson Reuters' Web of Science (WoS) Core Collection. This structured database indexes chosen papers from numerous disciplines to investigate current developments in photoelectrochemical and hydrogen research from 1970 to 2022. Compared to earlier reviews, this study undertakes further research by offering an integrated bibliometric analysis of published research on hydrogen and PEC techniques utilizing scientific mapping and a state-of-the-art review of PEC systems. A total of 936 samples of PEC and hydrogen publications were analyzed. It intends to identify the publication trend of

Table 1 – Instant of issued articles (1970–2022) in the WOS database by merging the title examines to keywords such as “systematic” and topic analysis to keywords such as “photoelectrochemical” and “water”.

No.	Year	Main focus	Ref.
1	2014	“Photoelectrochemical splitting of water with nanocrystalline Zn _{1-x} Mn _x O thin films: First-principle DFT computations supporting the systematic experimental endeavor” <ul style="list-style-type: none"> • For PEC water splitting, Mn-infused ZnO is a promising choice. • DFT-calculated electronic band structures backed up the experimental findings. 	[10]
2	2016	“Systematic comparison of different dopants in thin-film hematite (alpha-Fe ₂ O ₃) photoanodes for solar water splitting” <ul style="list-style-type: none"> • Systematic evaluation of the effects of various dopants without the presence of false side effects caused by differences in microstructure and morphology. 	[11]
3	2016	“Shape evolution of hierarchical W ₁₈ O ₄₉ nanostructures: a systematic investigation of the growth mechanism, properties and morphology-dependent photocatalytic activities” <ul style="list-style-type: none"> • Under solvothermal conditions, an additive-free synthesis of W₁₈O₄₉ with controlled morphological progression and phase transition was described. • The processes for morphological evolution have been suggested systematically. 	[12]
4	2017	“An efficient, visible light-driven, selective oxidation of aromatic alcohols and amines with O ₂ using BiVO ₄ /g-C ₃ N ₄ nanocomposite: a systematic and comprehensive study toward the development of a photocatalytic process” <ul style="list-style-type: none"> • The photocatalytic oxidation of benzyl alcohol, benzyl amine, and aniline utilizing O₂ as an oxidant was examined using BiVO₄ and g-C₃N₄. • The catalytic effectiveness of iVO₄ was compared to that of FeVO₄ and LaVO₄, two metal vanadates that have been extensively studied. 	[13]
5	2018	“Systematic investigation for the photocatalytic applications of carbon nitride/porous zeolite heterojunction” <ul style="list-style-type: none"> • The researchers devised a synthetic technique for the fabrication of TS-1/g-C₃N₄ nanocomposites. 	[14]
6	2019	“Systematic studies of Bi ₂ O ₃ hierarchical nanostructural and plasmonic effect on photoelectrochemical activity under visible light irradiation” <ul style="list-style-type: none"> • Various morphologies of β-Bi₂O₃ were synthesized at very low temperatures, and the influence of morphology and Ag plasmonic nanowires on their PEC water-splitting activity was examined. 	[15]
7		“Systematic material study reveals TiNb ₂ O ₇ as a model wide-bandgap photoanode material for solar water splitting” <ul style="list-style-type: none"> • Under illumination, the powder-based TiNb₂O₇ photoanodes have optimal water-oxidation kinetics and oxidize water with minimum applied biases. • TiNb₂O₇ has a photocurrent onset voltage (0.4 V vs. RHE) comparable to other state-of-the-art photoanode materials. 	[16]
8	2021	“Systematic study of an Fe ₂ O ₃ stacked homojunction photoelectrochemical photoelectrode” <ul style="list-style-type: none"> • The hotplate chemical bath deposition process was used to create Fe₂O₃ homojunction photoelectrodes. • On the Fe₂O₃ homojunction photoelectrode, the impacts of the buffer layer, the number of stacked layers, the stacked-layer structure, and the thermal annealing treatment procedure were comprehensively examined. 	[17]
9	2021	“A systematic study of post-activation temperature dependence on photoelectrochemical water splitting of one-step synthesized FeOOH CF photoanodes with erratically loaded ZrO ₂ ” <ul style="list-style-type: none"> • The researchers created a hematite cauliflower-like structure with unevenly loaded ZrO₂ (ZrO₂-Fe₂O₃ CF). • The impact of post-synthetic treatments on photoelectrochemical performance was thoroughly explored. 	[18]
10	2022	“Systematic exploration of WO ₃ /TiO ₂ heterojunction phase space for applications in photoelectrochemical water splitting” <ul style="list-style-type: none"> • WO₃/TiO₂ heterojunction stage space as a typical scheme was explored. 	[19]
11	2022	“A comprehensive systematic review on hydrogen production from photoelectrochemical water splitting via bibliometric analysis” <ul style="list-style-type: none"> • Investigation the publication trend and country collaboration and co-authorship. • Authors and occurrence network studies. • Subject category distribution for the literature. • Review the material used in the PEC systems for some detected papers • Challenges and perspectives 	Current research

papers in the area, identify the influential contributors in the PEC method, examine the co-authorship of different writers and nations, and analyze the co-occurrence of author keywords. A bibliometric analysis was conducted on PEC and hydrogen technologies utilizing various methodologies, such as frequency analysis, co-authorship network analysis, and keyword co-occurrence network analysis. These keywords aid in the deciphering of the essential paths in PEC and hydrogen research and the identification of new or understudied areas. A more extensive examination of the

method’s implementation in the area is required to develop research patterns, shared gaps, and best practices.

Search strategy and the protocol of the study

The bibliometric technique is the principle for representing the structure and activity of exploration and volume, and development in a particular subject [20]. The quantitative use of bibliometric data is known as a bibliometric approach [21].

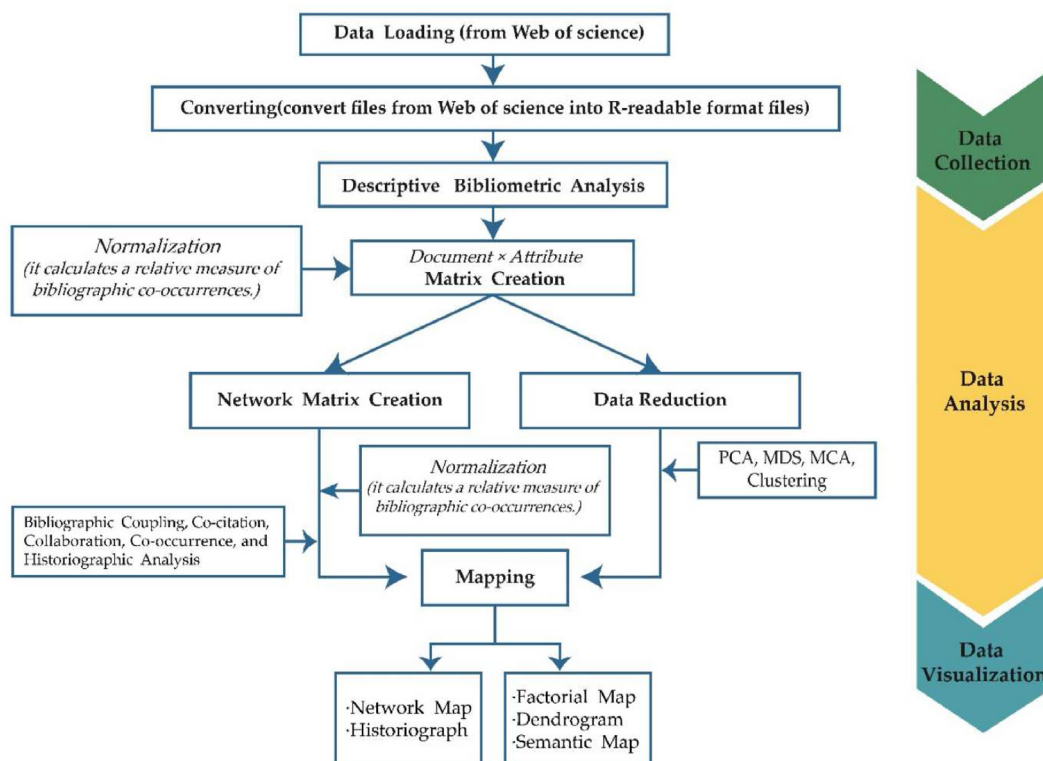


Fig. 2 – Bibliometrix and the recommended science mapping workflow [23].

and citations than a traditional research article. In addition to the typical research articles (796), the search result also included other types of publications such as editorial material (7), correction (3), proceedings papers (87), book chapters (10), books (1), meeting abstracts (38), early access (6) and notes (8). In terms of citations, the WoS has acquired 20,292 citations during the last ten years via its published publications. This research work contains the results and discussion of the findings, which reveal (i) in terms of publication production, citations, journal, distribution, the progress and trends in PEC and hydrogen research; (ii) productive researchers, relationships, and networks; and (iii) the field's thematic emphasis.

Publication growth and citation trends by countries

In this subdivision, we analyze the yearly technical generation of papers and citation trends in photoelectrochemical and hydrogen. Fig. 3 shows WoS's productivity trend as distinguished by the number of documents issued and cited annually. Specifically, between 1970 and 2022, 936 articles were published. From the 1970s to 2004, photoelectrochemical and hydrogen did not pique the interest of many scholars. The annual publishing productivity climbed slowly between 2005 and 2006, was followed by significant growth between 2012 and 2015, and an extremely sharp rise in 2013 before suddenly peaking in 2019. More recently, the number of publications drastically increased from 19 in 2009 to 79 in 2021, representing a growth rate of 415%. The month of February accounted for the most publications in 2022, and it ranked lower than in prior years. The number of articles starts to rise and continues to rise, notably noticeable in the twenty-first

century. To keep up with the growing number of citations, photoelectrochemical and hydrogen research has gotten increased attention in the previous decade. We identified 936 case reports and 20,292 citations. The quantity of case reports exhibited an upward trajectory over the years, reaching a peak in 2019, and this same trend was observed in the case of citations, peaking in 2020. In most cases, the type of article quoting the case reports has been an original article. It is also possible to visually represent the countries' collaboration network as a chord diagram. A chord diagram represents a group of things' directed relationships (flow or connection) (called nodes). Each entity is represented as a piece on the circular layout's periphery. Then, between each entity, arcs are drawn. The significance of the flow is proportional to the magnitude of the arc. Chord diagrams are visually appealing and often used in data visualization. The chord diagram has the advantage that all nodes are organized on a circle, and the edges from one node are gathered and bundled, eliminating the hairball issues that arise in the node-link diagram. They make it possible to see the weighted connections between various things. The countries are ranked based on their total link strength, and the respective countries determine the colors of individual chords depicted in the plot. Each chord in the diagram represents a grant and connects two or more countries where the research was conducted. The countries denoted in small nodes, such as France, Netherlands, Mexico, and Algeria, lack publication and collaborations with other countries. At the same time, it is also apparent that there is a large flow into photoelectrochemical and hydrogen research from countries such as China, the USA, Canada, Germany, and South Korea. In contrast, if we examine China, one can see a

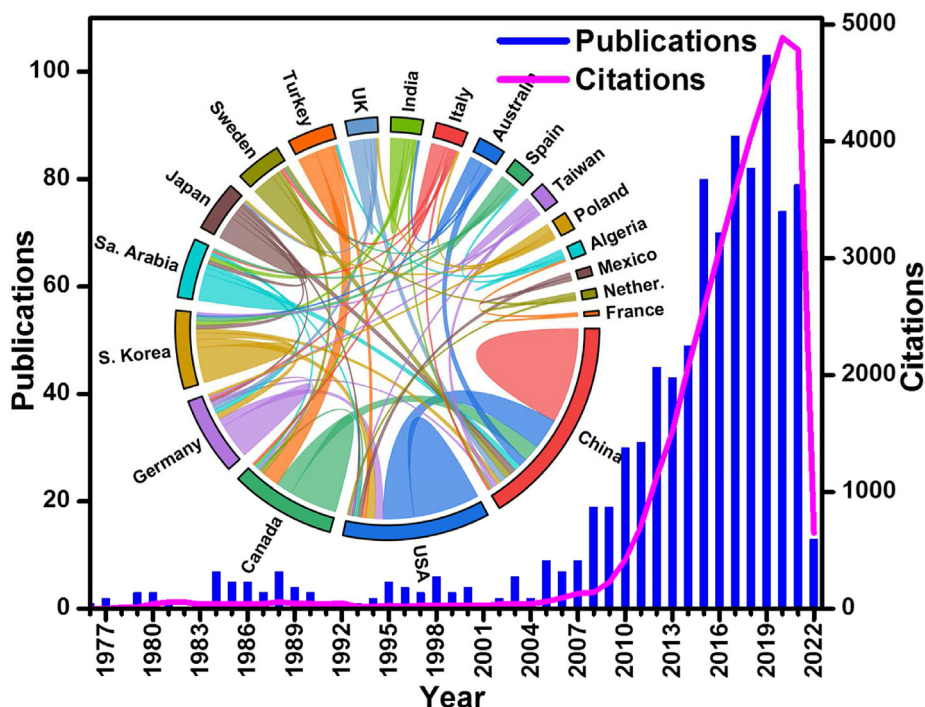


Fig. 3 – World annual growth rate and trends of publications and citations along with chord diagram for the title search of “photoelectrochemical”, and “hydrogen” from 1970 to 2022 as per 17th February 2022.

thicker blue line denoting flow into research collaboration within the USA, with a thinner line connecting to Germany, India, and Italy. To further thoroughly visualize the particular development evaluation, we conducted a Sankey figure in the following analysis.

Another important feature of Bibliometrix is the ability to plot a Sankey diagram to see numerous characteristics simultaneously. Sankey diagrams are useful for focusing on energy flow and distribution across various energy systems. Sankey Diagrams have been used in various methods in recent years to undertake multi-dimensional analysis that depicts energy flow [24]. Sankey Diagrams were initially employed on steam engines, but they have recently been

utilized on contemporary energy-producing systems such as power plants and global energy systems [25–27]. We employed a three-field plot, also known as the Sankey diagram, to assess the “flow” among the country (right), journals (left), and keywords (middle). The results visualize the interlinkages and the inter-dependencies in photoelectrochemical and hydrogen from 1970 to 2022. The top keywords frequently employed in the first material are: “photoelectrochemical” and “hydrogen”. The three-field plot, shown in Fig. 4, illustrates the flow trend between two or more entities. The arrow widths and the boxes in a three-field plot are proportionate to the associated quantity and numbers. The line's width and color are its aesthetic

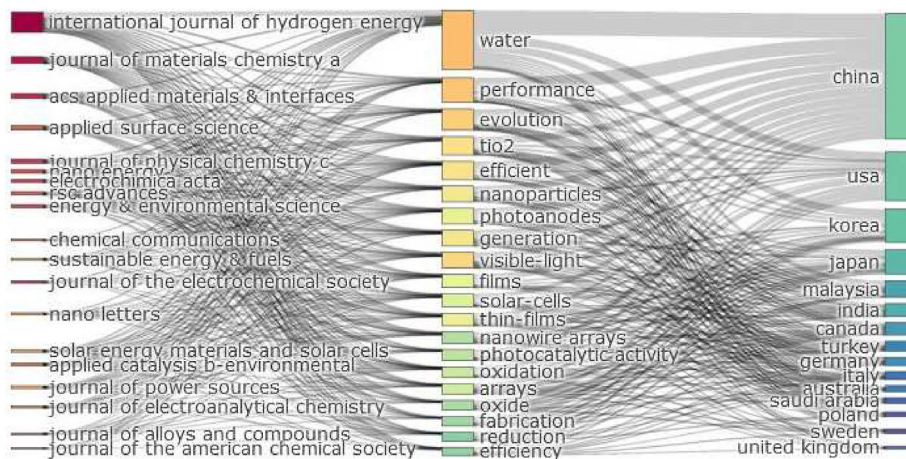


Fig. 4 – A three-field plot based on the Sankey diagram used to visualize the interactions among the most relevant country (right), source (left) and keywords (middle).

qualities, whereas the width of the colored bars shows the country's and sources' fraction of the total keywords created. The width is typically used to denote the number of exchanged keywords. The more significant the overlap between the two themes, the thicker the line. We can distinguish different research themes by using color. A collection of category colors is used to color the linkages, nodes, and trends. In Sankey diagrams, the linkages usually follow a gradient, shifting from the color of the left node to the color of the right node. Even though this is aesthetically pleasing, we chose to invert this gradient to make it easier to identify trends in one data set linked to a trend in the other data set. The figure shows that China is working with most of the top affiliations concerning topics related to photoelectrochemical and hydrogen. Furthermore, the other major contributors, like the USA, Korea, Japan, Malaysia, and India, have made significant contributions based on mentioned research in energy topics. Water is the dominant research topic in China, the USA, and Korea. The most famous articles in China were published by Wang et al. [28] (1992 citations) published in *Nano Letters* journal (Q1 and impact factor = 11.189), followed by Li et al. [29] (797 citations) and Ding et al. [30] (326 citations). Wang et al. [28] prepared TiO₂ nanowire arrays for PEC water splitting. They found that H:TiO₂ nanoparticles (anatase nanotubes and rutile nanowires) produced significantly improved photocurrent densities. Li et al. [29] reviewed the situation of capable photoelectrodes and techniques to increase their properties for solar hydrogen production via photoelectrochemical cells. They claim that by tuning the electrolyte, electrocatalyst, and photoelectrodes simultaneously, photochemical durability may be improved. They also advised that PEC seawater splitting of BiVO₄ be given greater consideration. BiVO₄ may be utilized as an exterior layer to increase the PEC endurance

of heterojunction photoelectrodes. Ding et al. [30] reviewed molybdenum disulfide (MoS₂) and similar compounds as low-cost electrocatalysts for hydrogen evolution reaction (HER) catalysis and PEC water splitting. Starting with the initial bulk MoS₂ catalyst, the HER catalytic activity and overall catalytic performance of MoS₂ and related compounds have been significantly improved, making them highly competitive earth-abundant and inexpensive alternatives to Pt and other noble-metal catalysts, even though their catalytic activity remains lower than Pt. The data behind the Sankey for the source of publications and more information about how to read the keywords connected with them are very essential. Researchers interested in efficiency, reduction, fabrication, and oxide may utilize our results to design investigations on the identified hot issues by evaluating research trends and research gaps in this area by examining the breadth of the connection running from the keywords to nations. Nevertheless, “water” and “performance” were covered more extensively by the *International Journal of Hydrogen Energy*. This is most likely because this publication is primarily concerned with technical advances and research findings in the area of hydrogen energy amongst scientists and engineers all over the globe. We also see that sources such as the *Journal of the American Chemical Society*, *Journal of Alloys and Compounds*, and *Journal of Electroanalytical Chemistry*, associated to other journals, have least and excessively contributed to the quantity of investigation, cover numerous themes key to PEC and hydrogen. Based on the three domains plotted in Fig. 4, it's impossible to tell whether research is carried out by individual countries or a group of countries in a collaborative project. We structured the worldwide cooperation map (Fig. 5), most cited countries (Fig. 6), and co-occurrence network visualization (Fig. 18) to display research collaborations and possible synergies between the two fields.

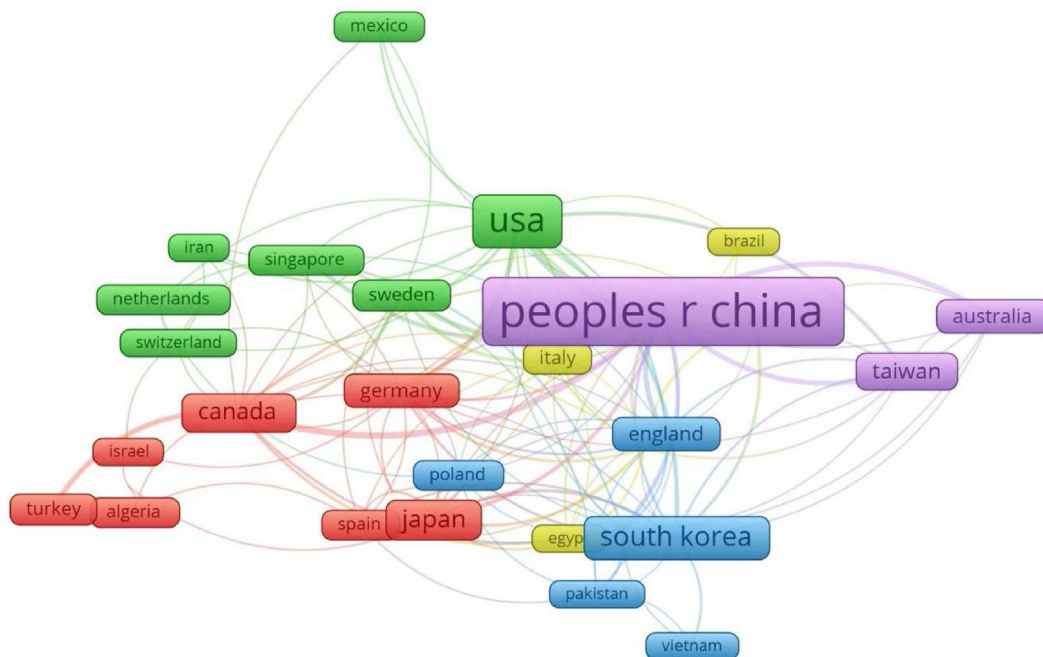


Fig. 5 – Bibliometric country collaboration map based on co-authorship on (Bibliometric map of co-authorship from VOSviewer using country).

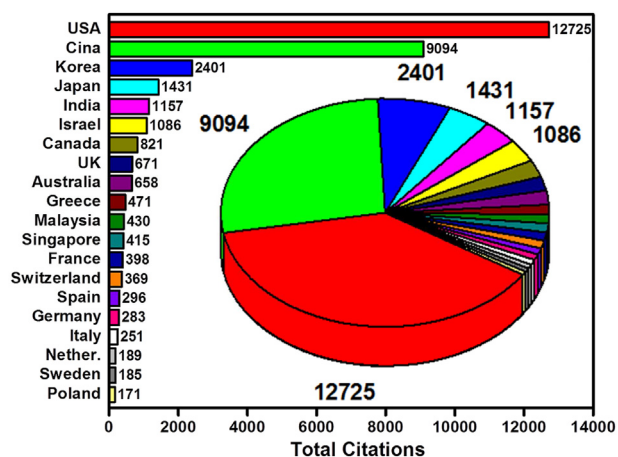


Fig. 6 – Most cited countries.

To further analyze the partnership association of publications in photoelectrochemical and hydrogen study, we make a co-authorship investigation by VOSviewer at the level of countries. The size of the frames represents the number of documents; the wider the frame, the more documents; the distance between two frames, the stronger the relatedness between them. Thus, the closer two countries are to each other, the stronger their scientific collaboration. In the international data sources searched, as shown in the chord diagram in Fig. 3, the bibliometric map of countries' co-authorship in Fig. 5, and the most cited countries in Fig. 6, it was possible to see the three countries which most published on photoelectrochemical and hydrogen were: China (114 total link strength, 300 publications, and 9094 citations), USA (57 total link strength, 171 publications, and 12,725 citations) and Canada (44 total link strength, 55 publications, and 821 citations), showing their high impact on the research. The maps

can also show the contribution of other countries to international production. The growing worldwide collaborative effort seems to align with the growing contributor base. Increased citations show that this evolution seems to have led to more effective work. The red and green clusters bring together European countries and territories with great connections. China, Taiwan, and Australia appear far from all other clusters, indicating weak ties with other countries in their networks. The USA is the most networked country, collaborating with 19 countries ($n = 19$), and it was the primary collaborator with other main prolific nations (China, South Korea, Japan, Canada, Germany, and the UK). Other countries such as China ($n = 18$), Germany ($n = 18$), Canada ($n = 17$), and the UK ($n = 14$) also have the highest betweenness centrality value within the network. Netherlands, Poland, and Switzerland have the lowest citations and weak networking between other countries. In Poland, research mostly worked on TiO_2 complexes as photoanode materials for PEC hydrogen generation. For example, Wysmulek et al. [31] employed photoactive layers of $\text{SrTiO}_3\text{-TiO}_2$ eutectic composite generated by the micro-pulling-down approach for solar-driven water splitting, and the reaction is seen schematically in Fig. 7. After 30 h of continuous analysis under difficult circumstances, they found no photocurrent failures and attained the greatest recorded value. Thus, the findings based on the bibliometric map of co-authorship point to the nations with the best chance of acting as research brokers within the network, as they can more easily mediate and distribute information or establish research contacts across countries. Internationally collaborative papers received more citations on average than articles generated by individual nations (Fig. 6), while the number of international collaborative articles may never equal the number of single-country articles. This underlines the importance of global networking and its influence on research output regarding international collaboration. These findings

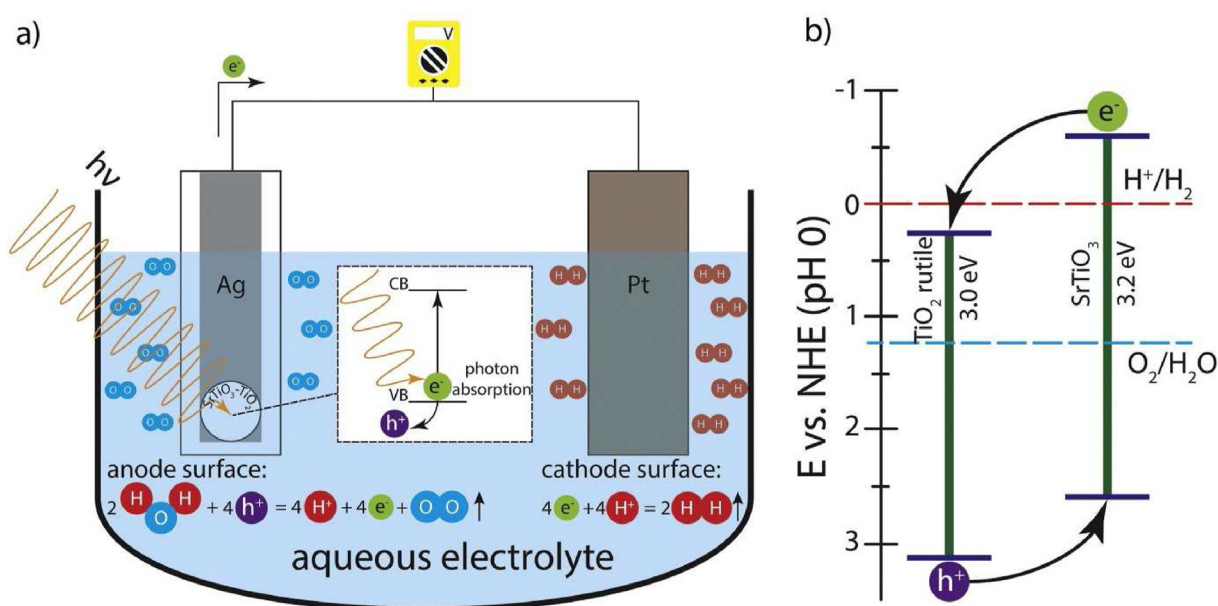


Fig. 7 – PEC cell diagram based on $\text{SrTiO}_3\text{-TiO}_2$ eutectic compound. a) A abridged PEC cell using a eutectic scheme as photoactive anode materials; b) the mechanism of charge-carrier splitting at the point boundary in a joined semiconductor $\text{SrTiO}_3\text{-TiO}_2$ method [31].

are consistent with earlier bibliometric studies in many domains, namely that the United States has the largest activity in global scientific research output and international cooperation networks and the highest h-index [32–34].

Authors, occurrence, and citation network

Because the sector's complexity encompasses many stakeholders and is increasingly reliant on transdisciplinary research, collaboration networks are significant in science and innovation. The interaction of two or more scientists in a social context that stimulates the sharing of ideas and the completion of tasks to pursue a shared objective is referred to as scientific cooperation [35]. Scientists may and should learn from one another to acquire a shared understanding of their research subject and combine their specialized expertise to generate new knowledge. Scientists must learn from one another due to increased specialization within research, the complexity of the infrastructure necessary, and the need to mix diverse knowledge and abilities to handle complex technical issues [35,36]. Scientific collaboration can also help broaden the scope of a research project and foster innovation as it provides access to different disciplines [37]. Despite the fact that there have been several previous studies on research cooperation, the topic of collaboration in PEC and hydrogen has gotten relatively little attention, as has the propriety of attempting to measure it via co-authorship [38,39]. Thus, in this section, we first observe the most productive authors and the correlations between them to understand and assess scientific collaboration patterns. Then, we proceed to compare the most frequent institutes and organizations and collaboration among them too. Co-authored scientific publications link authors in co-authorship networks as nodes. Each co-authored publication is represented by links, or edges, between the frames, and each author is represented by a frame in the network. The higher the association strength of two frames, the stronger the attractive force between the frames hence the closer they appear.

Authors' output and association

There are 3651 writers active in PEC and hydrogen research out of 936 publications, as shown in Fig. 8, where the most prominent authors are sorted by the number of documents published between 1970 and 2022 and are embedded in a pie with a varied radius. After setting the number of authors to 20 and utilizing the biblioshiny command of bibliometrix in RStudio software with a frequency measure based on the number of documents, it was observed that Ibrahim Dincer is the most productive scholar with 24 publications, followed by Yong Li (from Hefei University of Technology, China) and Sahab Dass (from Dayalbagh Educational Institute, India) with 19 and 17 publications, respectively. Dincer, Ibrahim from the Ontario Tech University of Canada primarily investigated the research on hydrogen production, water, solar energy, efficiency, membrane, PEC process, TiO₂ nanoparticle, etc. For example, Canan and Ibrahim [40] conducted a continuous-type hybrid PEC process for hydrogen generation, and a schematic flow diagram of the reactor is shown in Fig. 9. The liquid phase is present in the entrance Streams 1 and 4 and the output Streams 2 and 5. Streams 3 and 6 are in the gas phase at

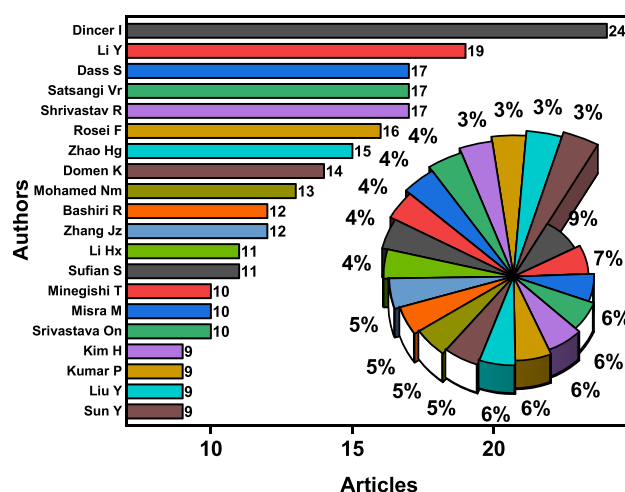


Fig. 8 – Most productive and influential authors with highest publications in PEC and hydrogen.

the outflow. The system's efficiency is improved by converting wastes into NaOH and Cl₂ gas, generating more money from numerous products. They suggested that future research consider the effect of temperature on system efficiency and losses. The parametric analyses based on operating and ambient temperatures can address and minimize any exergy losses in the system. Another top-produced author from China, Li, Y, mainly used keywords such as water, nanotube arrays, generation, performance, nanorods arrays, photocatalysis, graphene, TiO₂, etc. For an instant, Wang and co-workers [41] demonstrated the simultaneous hydrogen generation and electricity with simultaneous pollutants removal from “actual” urban wastewater within a dye-sensitized photoelectrochemical cell (DSPC). They employed nanostructured plasmonic Ag/AgCl @ chiral TiO₂ nano-sized fibers as photoanode and platinumized performing glass as cathode material for the DSPC system, and the schematic flow diagram is displayed in Fig. 10. Comparing the Ag/AgCl @ chiral TiO₂ nanofibers photoanode and the Ag/AgCl @ broken chiral TiO₂ nanofibers photoanode indicated the cooperative interplay between Ag nanoparticles and chiral nanofibers led to significant improvements in photoelectrical performance, rapid hydrogen production, and effective removal of pollutants. With continuous advancements in DSPCs for water-based usages, it could be able to improve the proficiency of energy production and pollutants elimination, and eventually apply them successfully in home and industrial wastewater treatment operations. Productivity and openness to collaboration for the most influential authors (Fig. 11) were visible in their co-authorship network.

Authors in co-authorship networks are connected as nodes through co-authored scientific articles. Each co-authored publication is represented by links, or edges, between the nodes, and a node in the network represents each author. To put it another way, researchers who are near one another are more likely to refer to the same articles, but researchers who are far apart are less likely. Measurements can be used to describe the network structure, such as author density or centrality [42]. Fig. 11 displays the linkage of cooperating

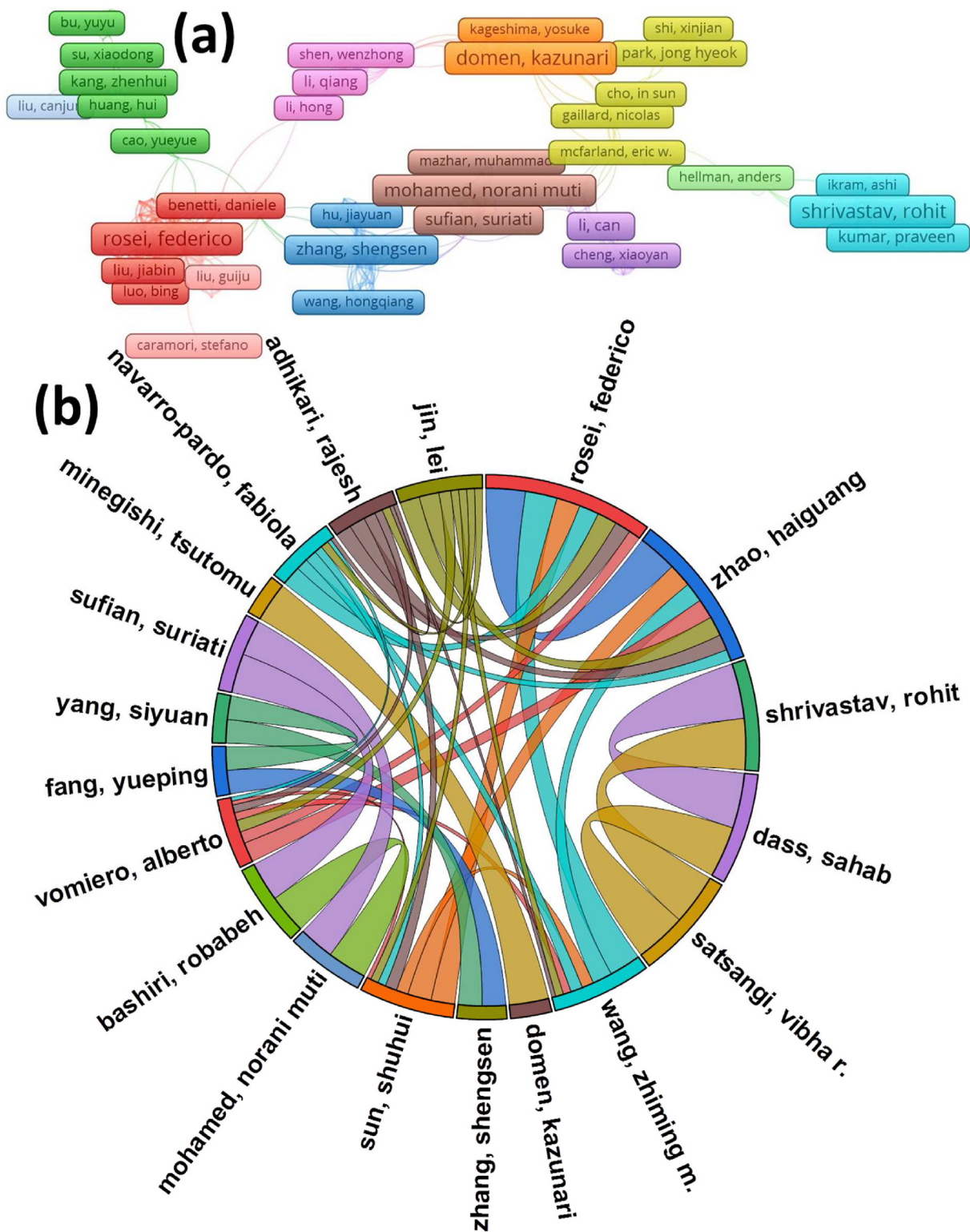


Fig. 11 – (a) Bibliometric map of co-authorship from VOSviewer using author names (note: Minimum number of documents per author: 2; 752 of the 3651 scholars link this limit), and (b) ChordLink co-authorship network of the top 19 authors with the highest total link strength.

(QDs), and TiO₂ nanotube arrays. Zhang et al. [45] employed optimized colloidal heterostructured quantum dots to generate photoelectrochemical hydrogen. By varying the shell thickness, they evaluated and plotted the optoelectronic

characteristics and band alignment in colloidal heterostructured CdS/CdSe core/shell QDs. They discovered that the intensity of Se/S peak ratios increased with increasing CdSe shell thickness, consistent with the CdSe shell's progressive

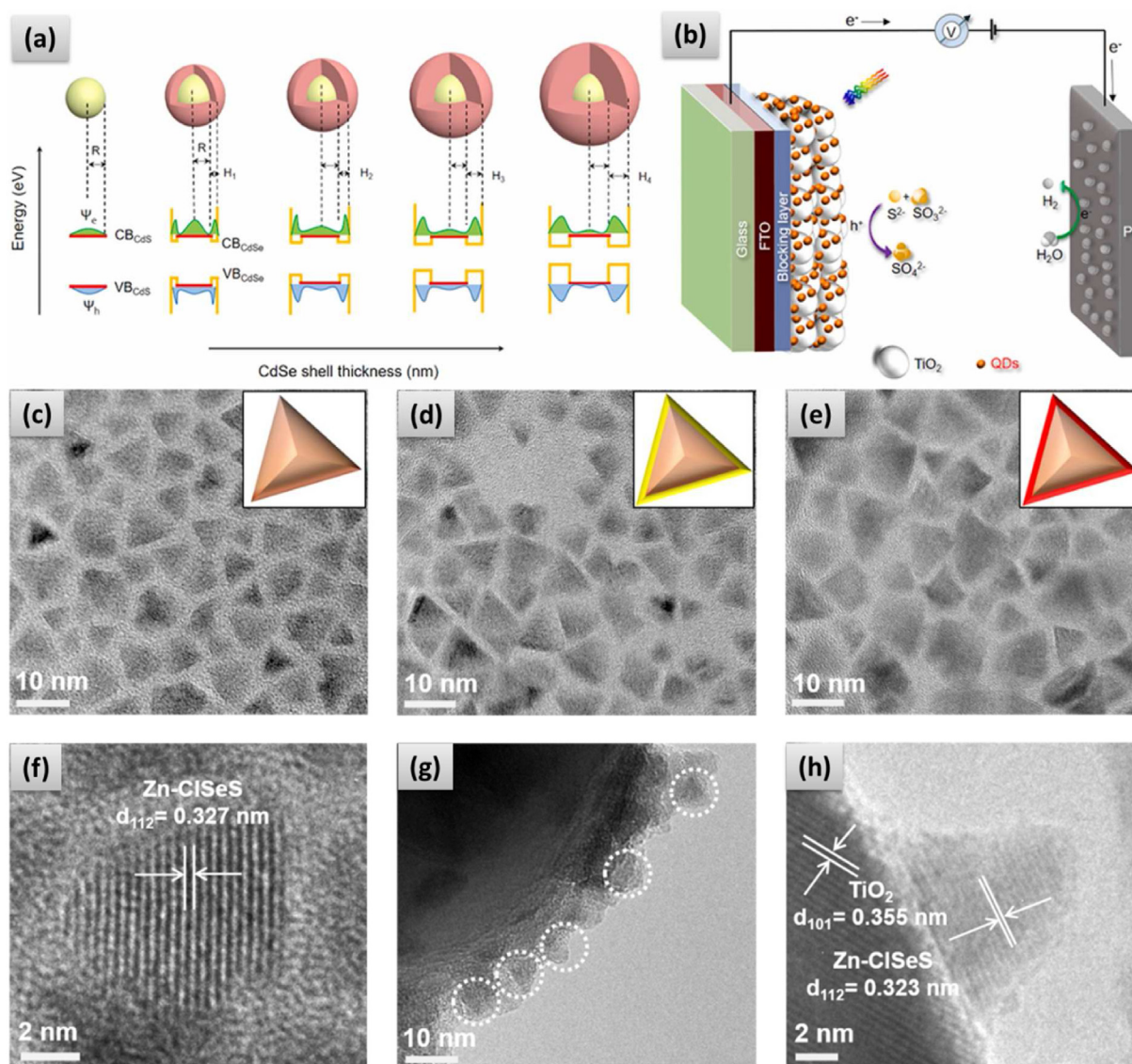


Fig. 12 – (a) Diagram of band placement of the core/shell and bare quantum dots (QDs) by alteration shell thickness. Green and blue regions represent the likelihood of electron and hole distributions with changing shell thickness; (b) a working mechanism diagram of a PEC device based on TiO_2 nanoparticle mesoporous anode prepared colloidal heterostructured CdS/CdSe core/shell QDs [45]. TEM pictures of (c) $\text{CuInSe}_x\text{S}_{2-x}$ (CISeS) QDs; (d) Cd–CISeS, and (e) Zn–CISeS QDs have a pyramidal structure similar to Zn–CISeS QDs and are almost the same size. The schematic schematics of QDs structures of CISeS, Cd–CISeS, and Zn–CISeS are shown in the inset photos of (c), (d), and (e), respectively. (f) HRTEM figure of a specific Zn–CISeS QD with a lattice spacing of 0.327 nm. (g) TEM photo of $\text{TiO}_2/\text{Zn–CISeS}$ heterostructure with constant dispersion of Zn–CISeS QDs (single QD on the surface of TiO_2 is shown by the white dashed circle). (h) HRTEM of $\text{TiO}_2/\text{single Zn–CISeS QD}$ heterostructure (picture of the white line circle with higher magnification (g)) [44]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

expansion. Fig. 12 (a) depicts the development of CdSe shells of various thicknesses on the size and electronic band structure alignment of core/shell QDs. Fig. 12 shows a schematic representation of PEC cells with as-prepared QDs acting as light harvesters (b). When the QDs are illuminated, they absorb solar light and produce excitons. Photoexcited exciton dissociation occurs at the QDs/ TiO_2 interface, allowing photoexcited electrons in the QDs conduction band to be successfully injected into the TiO_2 conduction band. The TiO_2 mesoporous film transports electrons, while the luorine

doped tin oxide (FTO) layer collects charges, which are subsequently transmitted via the external circuit to the Pt counter electrode, where H_2 is generated. Tong et al. [44] used heavy metal-free near-infrared colloidal quantum dots for effective photoelectrochemical hydrogen production. The CISeS QDs had a triangular projected form in TEM images, as shown in Fig. 12 (c), implying a pyramidal shape with an average size of 5.64 nm (± 0.77 nm), where size is defined as the height of the projected triangles. Fig. 12 (f) shows a high-resolution transmission electron microscopy (HRTEM) picture of a single

Zn–CISeS QD. The observed lattice spacing of 0.327 nm is compatible with the (112) plane of alloyed CISeS QDs and sits between 0.319 nm (indexed to the (112) plane of pure CuInS₂) and 0.335 nm (indexed to the (112) plane of pure CuInSe₂), showing the alloy nature of CISeS. Fig. 12 (g) displays the TiO₂/Zn–CISeS heterostructure, which reveals that the QDs are evenly attached to the surface of TiO₂ nanoparticles with no visible agglomeration. The HRTEM picture of QDs/TiO₂ (Fig. 12 (h)) shows a close bond between QDs and TiO₂ nanoparticles, implying the potential of a rapid electron transfer rate from QDs to TiO₂, consequently increasing the performance of the QDs-sensitized PEC device by reducing exciton recombination. According to Liu et al. [43], hybrid ligand engineering is a possible route to high-performance PEC cells for hydrogen production. Future research should use different ligands to modify the surface of colloidal QDs to improve the performance of PEC cells and other optoelectronic devices.

Cluster 2 in green color mainly comprises Yuyu Bu (from Xidian University of China), Zhenhui Kang (from Soochow University of China), Fang Wang (from Shanxi Normal University of China), and Yueyue Cao (from Shanxi Normal University of China). Yueyue Cao and Fang Wang contributed to an article on glucose and hydrogen peroxide detection by AuNi nanodendrite arrays as photoelectrochemical biosensors [46]. The hierarchical structure of AuNi nanodendrite arrays with plentiful active sites and the plasmonic influence of Au with a high absorption band in the visible range can be ascribed to their much-improved performance. This newly created approach, which is inexpensive and straightforward, is critical in developing plasmon-assisted photoelectrochemical biosensors. The blue cluster number 3 contains Shengsen Zhang (from South China Agricultural University), Hongqiang Wang (from Northwestern Polytechnical University of China), and Jiayuan Hu (from the South China University of Technology) in bigger frames. Shengsen Zhang and Jiayuan Hu contributed to a photoelectrochemical hydrogen production article and loaded MoS₂ supported on anatase/rutile TiO₂ heterophase structure film (A-H-RTNA) as photocathode [47], and the schematic flow diagram is shown in Fig. 13. They synthesized a novel MoS₂/A-H-RTNA electrode with a twice higher hydrogen generation rate than Pt/A-H-RTNA. Instead of using a Pt electrode, the synthesized MoS₂/A-H-RTNA film was employed as a photocathode to create a new and efficient PEC system that forecasts a PEC approach without precious metals and has a wide range of applications. Cluster number 4, in yellow color consists of Jong Hyeok Park (from Yonsei University of Korea), Xinjian Shi (from Sungkyunkwan University of Korea), In Sun Cho (from Ajou University of Korea), Nicolas Gaillard (from the University of Hawaii in the USA) and Eric W. Mcfarland (from the University of California, USA). Authors in this cluster mainly worked on research with the most frequent keywords such as water, performance, efficient, TiO₂, photoanodes, nanoparticles, CdS and BiVO₄, and low frequency such as tungsten carbide. Cho et al. [48] proposed a unique dual heterostructured photoanode comprised of CdS@CdSe core-shell nanoparticles (NPs) and 1D-structure tin-doped indium oxide (ITO)@TiO₂ core-shell nanowires (ITO@TiO₂@CdS@CdSe) for very efficient PEC hydrogen generation, and the schematic diagram of the system is shown in Fig. 14 (a). In contrast to the reversible hydrogen electrode

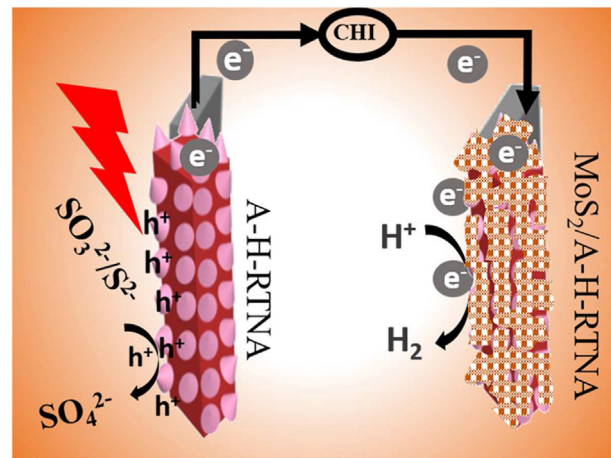


Fig. 13 – Schematic flow diagram of photoelectrochemical hydrogen generation using photocathode base on supported hydrogenated TiO₂ heterostructure film by MoS₂. Reuse with permission from Ref. [47].

(RHE), the dual heterostructured photoanode exhibited a maximum photocurrent density of 20.11 mA/cm² at 1.23 V and demonstrated a noteworthy enhancement in incident photon-to-current efficiency (IPCE) across the entire absorption spectrum. The effective separation of photoexcited charge carriers was achieved by the favorable cascade charge transport across the aligned energy band edges and rapid charge extraction within the hierarchical heterostructure. Other high-profile writers, such as Jong Hyeok Park and Xinjian Shi [49], collaborated to show a new BiVO₄-embedded mesoporous WO₃ bulk-heterojunction as a photoanode in a tandem cell with high solar-to-hydrogen efficiency (Fig. 14 (b)). An extraordinarily high solar-to-hydrogen (STH) conversion efficiency with spontaneous hydrogen evolution was achieved by combining highly transparent BiVO₄-sensitized mesoporous WO₃ films with a state-of-the-art water oxidation catalyst and a single dye-sensitized solar cell with a high open-circuit potential in a monolithic tandem configuration. They claimed that their concepts and technologies might be applied to various photoelectrodes other than the WO₃/BiVO₄ system, and that they will be essential for advancing PEC water splitting. Cluster number 5 in purple color comprises authors such as Can Li (from the Dalian Institute of Chemical Physics, China), Lianzhou Wang (From the University of Queensland, Australia), and Xiaoyan Cheng (Beijing Institute of Technology, China). For example, can Li and Xiaoyan Cheng contributed to a paper on plasmonic Au/CdSe nanodumbbells for photoelectrochemical hydrogen production beyond the visual range [50]. Under vis–NIR light irradiation, the unique nano dumbbell Au/CdSe HNRs can react across a broad spectral range and absorb more photons, resulting in high PEC H₂ production activity and a high STH of 2.38%. The researchers posit that this study will facilitate the development of a novel category of solar energy conversion materials by enabling the synthesis of multi-component nanostructures featuring unconventional topologies and functionalities. Lianzhou Wang and co-authors worked on multi-layered p-type Cu₂O photoelectrodes with plasmonic Au@TiO₂ for PEC

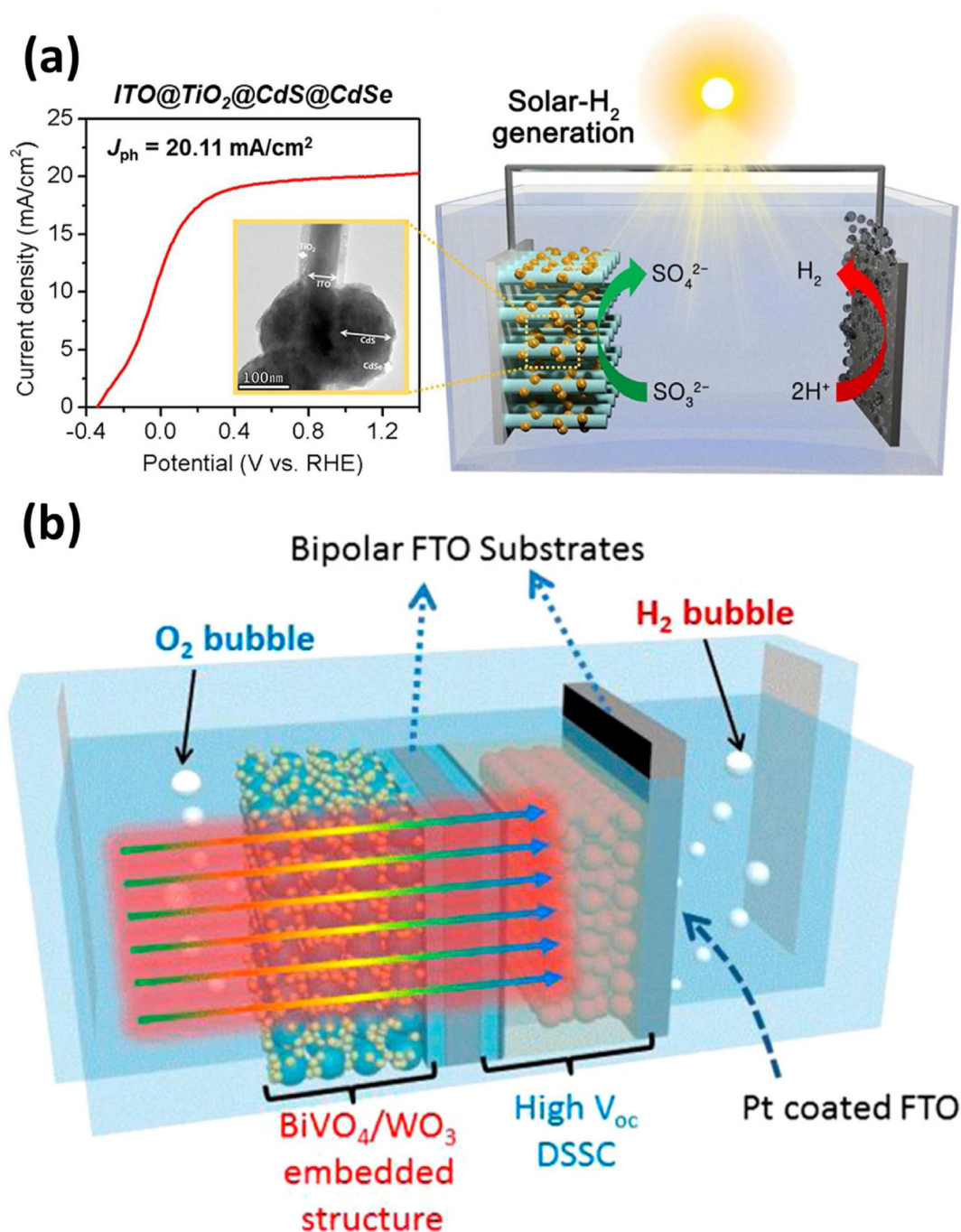


Fig. 14 – (a) Diagram drawing of the ITO@TiO₂@CdS@CdSe for the solar-H₂ generation reaction [48], (b) the cycle cell outline, which includes a structured WO₃/BiVO₄ photoanode that improves light absorption and transmission [49].

hydrogen production [51]. They contributed with Can Li in hydrogen peroxide production and hydrogen sulfide oxidation in an unbiased solar photoelectrochemical cell [52].

The light blue cluster number 6 mainly contains Praveen Kumar (from CSIR–Central Electrochemical Research Institute, India), Rohit Shrivastav (from Dayalbagh Educational Institute, India), and Ashi Ikram (from Dayalbagh Educational Institute, India). The primary authors in cluster 7 in orange were from the University of Tokyo, Japan, Kazunari Domen, and Takashi Hisatomi. They mostly contributed to LaTiCu photocathodes for PEC hydrogen evolution [53–55]. They

studied the influence of particle magnitude of La₅Ti₂CuS₅O₇ (LTC) on PEC properties in solar hydrogen production (see Fig. 15 (a)) [55], and the more fabulous LTC elements were found to produce a developed photocurrent. They discovered that using well-grown, rod-like LTC particles benefits PEC hydrogen generation. They also synthesized La₅Ti₂CuS₅O₇ (LTC) and La₅Ti₂AgS₅O₇ (LTA) solid solutions for the PEC water splitting reaction, and the schematic flow diagram is shown in Fig. 15 (b) [53]. Regardless of the Ag concentration, photoelectrodes of Al-doped LTC_{1-x}A_x solid solution powder produced using the particle transfer approach showed a

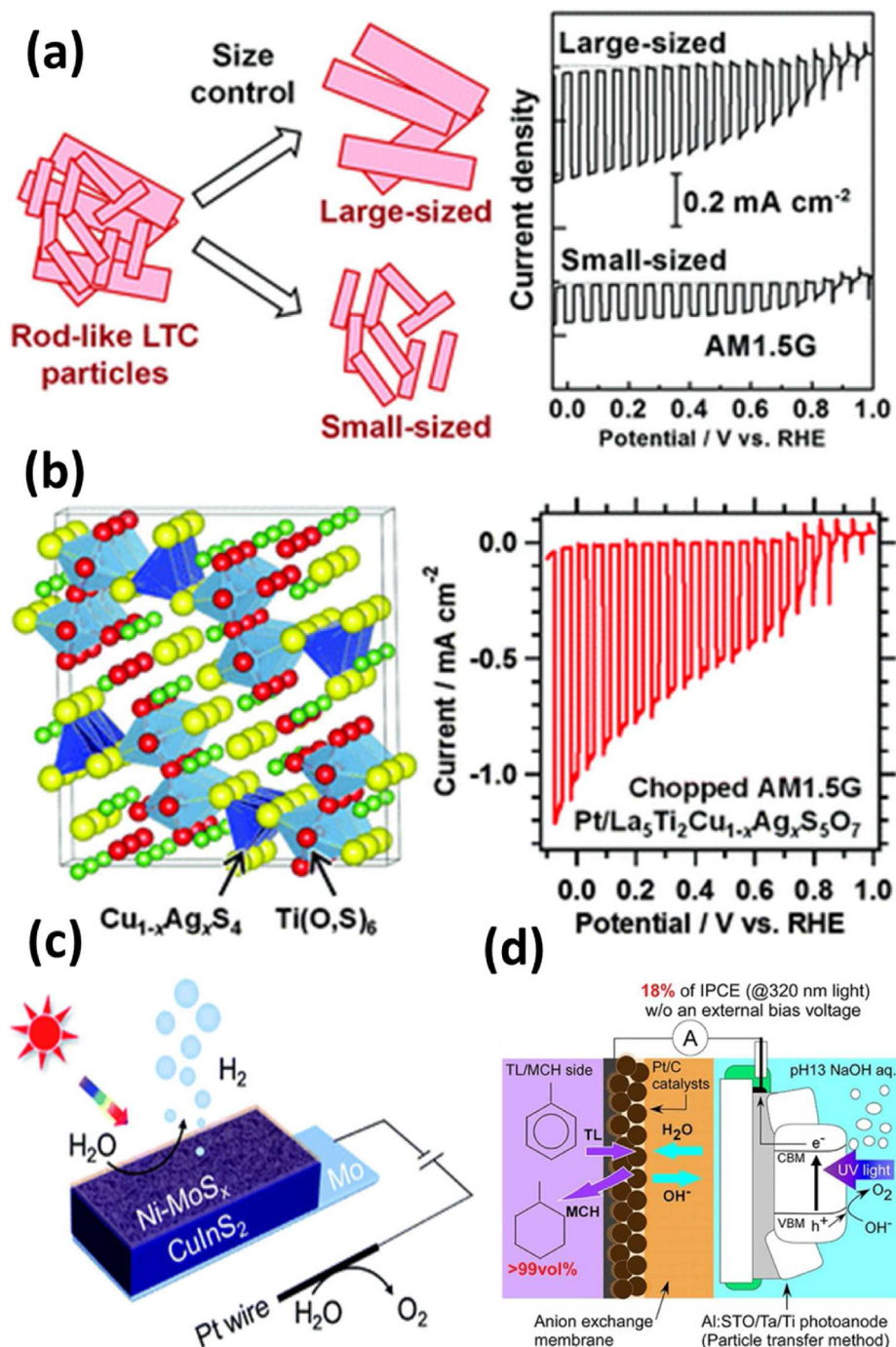


Fig. 15 – (a) Effect of LTC particle size on solar hydrogen development photoelectrochemical characteristics [55]; (b) $\text{La}_5\text{Ti}_2\text{Cu}_{1-x}\text{Ag}_x\text{S}_5\text{O}_7$ ($\text{LTC}_{1-x}\text{A}_x$) photocathodes functioning at positive possibilities for PEC hydrogen progress [53]; (c) CuInS_2 photocathodes improved with amorphous Ni-MoS_x operating in a neutral electrolyte for PEC hydrogen generation [56]; (d) PEC cell with a Pt/C-based membrane electrode and a particulate SrTiO_3 photoanode converted toluene and water efficiently and selectively into the hydrogen carrier methylcyclohexane [57].

photocathodic response. In the hydrogen evolution process, 1%Al-LTC_{0.9}A_{0.1} photocathodes had the best PEC characteristics. Most other frequent keywords in their research were electrodes, Ag, Cu, efficient, sunlight, thin-film, and etc. For PEC hydrogen generation, they used CuInS_2 photocathodes modified with amorphous Ni-MoS_x working in a neutral

electrolyte (Fig. 15 (c)) [56]. Between the CuInS_2 and Ni-MoS_x layers, a junction emerges, improving charge separation and allowing for efficient PEC hydrogen generation. As a result, instead of CdS, Ni-MoS_x films might be utilized as buffer layers for efficient and stable PEC hydrogen generation. Last but not least, they used PEC to convert toluene and water into

concentrated methylcyclohexane as a hydrogen carrier (Fig. 15 (d)) [57]. Their research showed that the current PEC system could produce concentrated methylcyclohexane, a potential hydrogen carrier. Methylcyclohexane production from toluene and water may be used to simulate photosynthesis.

Cluster 8, in brown color, mainly comprises Norani Muti Mohamed (Universiti Teknologi Petronas, Malaysia), Suriati Sufian (Universiti Teknologi Petronas, Malaysia), and Muhammad Mazhar (Fatima Jinnah Women University, Pakistan). The most frequent keyword with higher total link strength for Norani Muti Mohamed and Suriati Sufian collaborative publications were PEC cell, H_2 , water, Cu–Ni, TiO_2 nanorod, $BiVO_4$, thin-film, etc. One of their work by Bashiri et al. [58] prepared Cu–Ni/ TiO_2 photoanodes for PEC hydrogen generation, and the schematic diagram is displayed in Fig. 16

(a). They paired the PEC cell with the produced dye-sensitized solar cell (DSSC) module. The intermediates from the glycerol photooxidation were confirmed using high-performance liquid chromatography, suggesting partial glycerol oxidation through a selective route in KOH (1 M) solution. The superior physicochemical characteristics of TiO_2 , including crystallinity, crystallite size, specific surface area, surface state, and oxygen vacancy, contribute to a reduction in charge transfer resistance and an elevation in electron lifespan and charge carrier densities within the photoelectrode. Norani and Suriati tinkered with the morphological structure of the $BiVO_4$ photocatalyst to improve photoelectrochemical solar hydrogen generation from natural lake water (see Fig. 16 (b)) [59]. According to the findings, the $BiVO_4$ photocatalyst developed at $pH = 1.96$ and a hydrothermal temperature of $120^\circ C$ produced the most photocatalytic hydrogen from real lake water. Lower

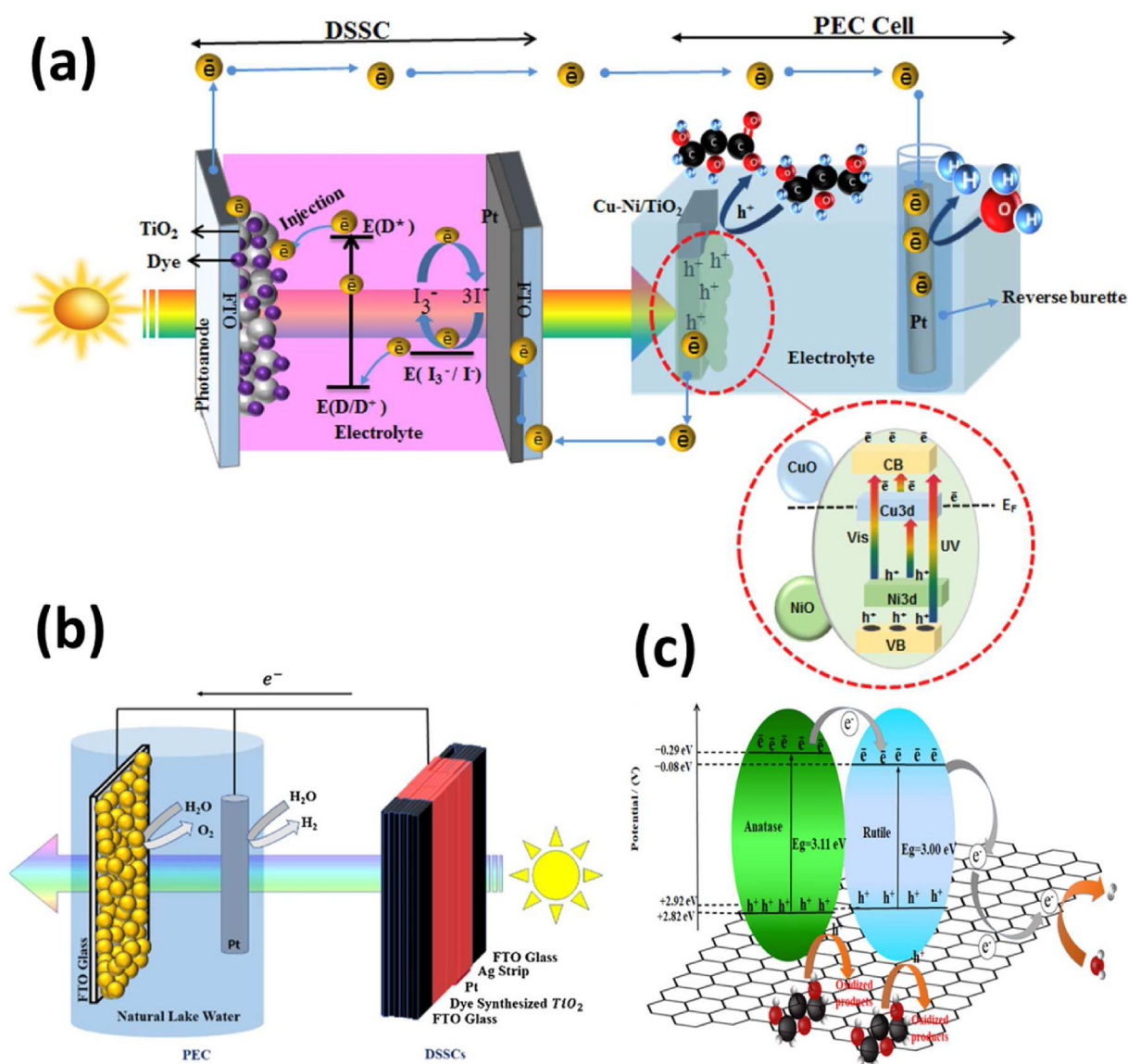


Fig. 16 – (a) Graphic illustration of the photocatalytic hydrogen evolution in the existence of glycerol in PEC/DSSC formation; (b) photocatalytic hydrogen synthesis from water splitting over $BiVO_4$ thin film using PEC/DSSCs [59]; (c) Graphic displaying the charge transfer and separation in the STNR@rGO photoanode complex for the hydrogen generation under visible light irradiation [60].

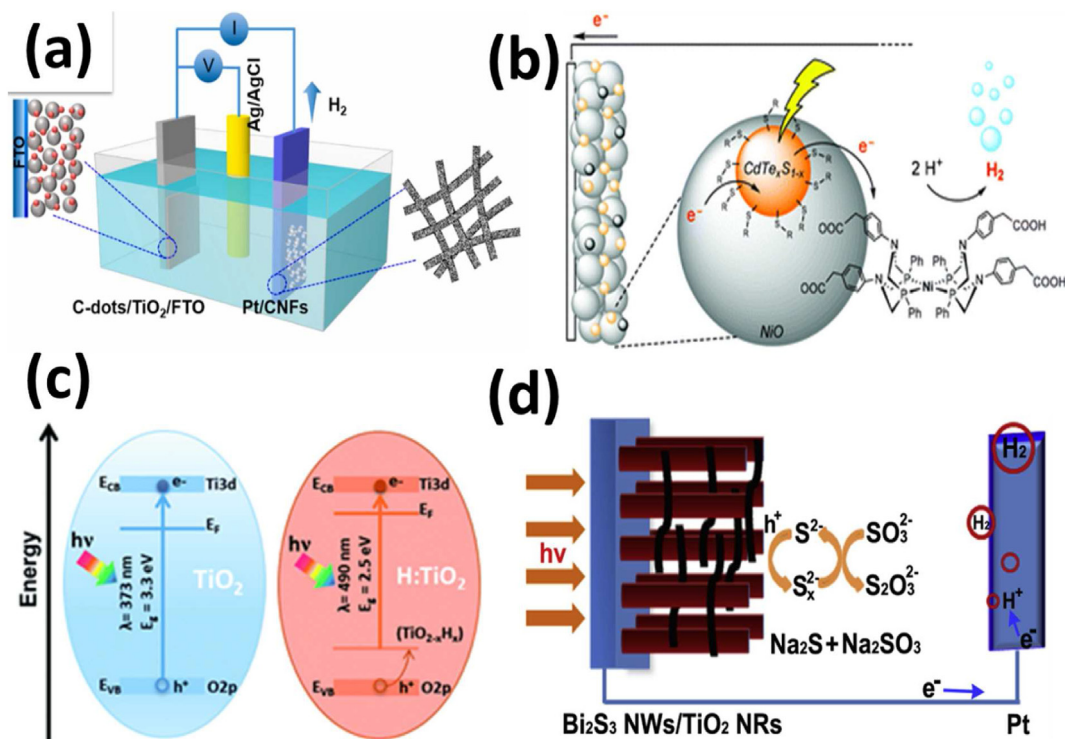


Fig. 17 – (a) Graphic illustration of a characteristic PEC system employing glucose aqueous solution as an electrolyte, Ag/AgCl as reference electrode, Pt/CNFs as a counter electrode, and C-dots/TiO₂ as anode [65]; (b) PEC hydrogen evolution utilizing CdTe_xS_{1-x} quantum dots as sensitizers on NiO photocathodes [66]; (c) band illustration depiction of pristine and hydrogen treated TiO₂ [67]; (d) graphic description for the process of PEC hydrogen production over novel Bi₂S₃ nanowire @ TiO₂ nanorod [68].

recombination resistance, improved morphology, and smooth photogenerated charge carrier separation and migration improved photocatalytic efficacy. Another collaborative study by the same co-authors (Fig. 16 (c)) prepared surface scattered TiO₂ nanorod (STNR) inscribed with reduced graphene oxide (rGO) for PEC hydrogen production [60]. When compared to rutile or anatase TiO₂@rGO composites, seeded TiO₂ nanorod@ rGO composites generated maximum accumulative hydrogen of 1200 mmol/cm² in a photoelectrochemical cell containing 1 M KOH and 5 vol percent glycerol under visible light irradiation. This intense photocatalytic activity is thought to be attributable to a synergistic contribution of direct electron transport between the anatase and rutile TiO₂ phases, rGO's high electron mobility, and the enhanced surface area formed by the TiO₂ nanorods.

Cluster 9, in pink color primarily includes authors from Shanghai Jiao Tong University of China, such as Wenzhong Shen, Qiang Li, and Hong Li. Wenzhong Shen and Qiang Li collaborated in research such as three-dimensional gallium phosphide nanopore arrays for improved PEC hydrogen generation [61], three-dimensional indium phosphide nanopore arrays for improved PEC hydrogen production [62], and Pt nano-sized particle decorated indium phosphide nanopore arrays for improved PEC activity [63]. Zhu et al. [64] mutually worked on an article titled “electrochemically etched triangular pore arrays on GaP and their photoelectrochemical properties from water oxidation”. Authors in the least appeared clusters were also detected, such as cluster number

10 in light red color such as Guiju Liu (from Qingdao University, China) and Stefano Caramori (from University of Ferrara, Italy); cluster 11 in green for Anders Hellman (from Chalmers University of Technology, Sweden); cluster 12 in light grey color that contains Canjun Liu (from Central South University, China); and last cluster number 13 in light yellow color (almost disappeared behind the light blue cluster) contain mainly Vibha Rani Satsangi (from Dayalbagh Educational Institute, India). Guiju Liu's study on colloidal carbon quantum dots as a light absorber for efficient and steady photoelectrochemical hydrogen production was one example (Fig. 17 (a)) [65]. They created an eco-friendly PEC device for hydrogen generation that used R C-dots/TiO₂ as an efficient and stable anode, glucose as an electrolyte, and Pt over carbon nanofibers (CNFs) as a cost-effective and efficient counter electrode. The hydroxyl group on C-dots may significantly interact with TiO₂, generating a highly stable compound instead of carboxyl capped C-dots. Stefano Caramori synthesized CdTe_xS_{1-x} quantum dots as sensitizers on NiO photocathodes for PEC hydrogen evolution (Fig. 17 (b)) [66]. The functionalization of NiO|QDs electrodes with either heterogeneous Pt or the molecular nickel bis(diphosphine) complex as hydrogen evolving catalysts (HECs) results in active photocathodes stimulating hydrogen evolution upon photoirradiation, according to the researchers. Anders Hellman and colleagues used first-principles calculations to study a simplified Fe₂O₃-TiO₂ heterostructure [67]. Representation places of band limits of TiO₂ and H:TiO₂ are displayed in Fig. 17 (c). Compared to pure TiO₂,

502, respectively. These are all the keywords whose occurrence is greater than 85. The relationships between “water” and “performance,” as well as “visible light” and “solar-cells,” imply the close integration of water-splitting research and the PEC technique. The least frequent keywords mean lacking research in those areas and help predict future tendencies. The frequent least keywords were “cathode”, “glucose”, “silicon photoanodes”, “cuprous-oxide”, “sensation”, “solvo-thermal synthesis”, “H₂S”, “n type gan”, and “electrolytes”. In the analysis of the co-occurrence of authors' keywords-plus, 217 out of 1489 keywords met the threshold with a minimum of five occurrences, producing seven clusters, 6009 links, and a total link strength of 12,308. By conducting co-occurrence analysis on keywords, we obtained a network consisting of water (cluster 1; 206 links, 1642 total link strength, and 325 co-occurrences), visible-light (cluster 2; 150 links, 522 total link strength, and 97 co-occurrences), efficient (cluster 3; 152 links, 547 total link strength, and 89 co-occurrences), generation (cluster 4; 156 links, 502 total link strength, and 85 co-occurrences), performance (cluster 5; 173 links, 753 total link strength, and 125 co-occurrences), photoanodes (cluster 6; 130 links, 427 total link strength, and 72 co-occurrences), photoanode (cluster 7; 111 links, 273 total link strength, and 46 co-occurrences) new types of platforms seven clusters in sequence. Seven systematic clusters on PEC and hydrogen investigation might be renowned by expending seven different colors. Cluster 1 in red consisted of research on water, films, arrays, nanostructures, and fabrication. Heavy metal-free, near-infrared colloidal quantum dots for efficient photoelectrochemical hydrogen production was the most referenced work in this cluster [44]. Overall, the Zn–ClSeS QDs are a promising system for solar-driven hydrogen generation that is environmentally friendly, cost-effective, durable, and highly efficient, opening the way for further research into green QDs for high-performance PEC systems. To enhance the efficiency and stability of PEC devices, future research efforts should focus on modifying the QD composition, such as CuSnSeS and CuZnSeS QDs, on increasing electron transport and engineering the shell structure (ZnSeS or ZnSe, etc.) and shell thickness. The green cluster number 2 mostly focused on visible light, photocatalytic activity, solar cells, thin films, and nanowire arrays. One of the most popular papers in this cluster prepared CoSe₂ and NiSe₂ nanocrystals (NCs) as great multifunctional catalysts for the coinciding production of H₂ and O₂ in water-splitting reactions [69]. They are very stable in harsh acidic and basic conditions, although CoSe₂ has stronger electrocatalytic activity than NiSe₂ in hydrogen evolution processes. The Co ions in CoSe₂ were more metallic than the Ni ions in NiSe₂, according to XPS and XAS data, which explains their greater HER catalytic power. NiSe₂ NCs are appealing options for realistic solar fuel generation because of the number of materials and active, steady catalytic power. The research in cluster 3 in blue color mainly concentrated on efficiency, evolution, graphene, catalysts, nanosheets, and photocathodes. The popular, published article in cluster 3 worked on chemically exfoliated metallic MoS₂ and Si heterostructures for PEC hydrogen production [70]. The good performance of the chemical vapor deposition (CVD) generated 1T-MoS₂/p-Si photocathodes may be ascribed to modest charge transfer

resistances across the semiconductor/catalyst and catalyst/electrolyte interfaces, according to electrochemical impedance spectroscopy (EIS) tests.

The fourth cluster in yellow color principally comprised generation, efficiency, enhancement, design, TiO₂, oxidation, and degradation. We have found nine published papers by employing keywords such as generation, efficiency, TiO₂, oxidation, and degradation in the All Fields search and merged them with the title search of photoelectrochemical and hydrogen. Sun and Yan [71] developed highly ordered TiO₂ nanotube arrays for hydrogen production in a two-compartment photoelectrochemical cell by anodic oxidation of Ti foil under varied anodization voltages in ethylene glycol electrolyte. Without any externally applied voltage or sacrificial agent, efficient hydrogen production may be obtained by splitting water in the two-compartment PEC cell. The anodization voltage has a linear relationship with the photocurrent responsiveness, photoconversion efficiency, and hydrogen generation of TiO₂ nanotubes, consistent with the result of layer thickness. Cluster 5, with its purple color, is mainly associated with keywords such as performance, nanoparticles, CdS, composite, deposition, and semiconductors. The studies in cluster 6 with light blue color mostly worked on photoanodes, photocatalysts, growth, electrodes, and photo-oxidation. The last cluster in orange color generally concentrated on photoanode, heterojunction, surface passivation, and graphitic carbon nitride. The search keywords for cluster number 7 detected only one paper published by Xu et al. [72] that worked on preparing InGaN nanorods (NRs)/C₃N₄ heterojunction photoanode for boosted charge separation and interfacial charge transfer to boost PEC water splitting. The approach is versatile and easy to use, allowing C₃N₄ nanosheets to be loaded onto various substrates, notably those with a low dimensional structure. With tiny circles in each cluster, the network representation shows a similar separation into subfields. The models have changed slightly, particularly in how the subfields are placed concerning one another and how considerable information is provided.

Challenges and perspectives

There are a limited number of publications regarding photo-reactors for PEC water splitting, as significant effort is still being directed toward improving the efficiency and stability of the photoelectrode. By identifying collaborative writers who have played significant roles in the academic community around the PEC area, this study may aid academics, students, policymakers, and managers in developing a theory of PEC and hydrogen. The absence of an explanation of cooperation with co-authorship [73] and the subjective nature of visualization interpretation [74] are two methodological flaws in this study's co-authorship analysis. We only included literature from the WoS database. Future studies with other databases like Scopus will benefit from a more comprehensive study with bibliometric analysis. Another limitation is that we only considered English-language articles published in journals. This is because the authors are English speakers and needed to review all the literature to include those that met the

eligibility criteria. The results are based solely on systematic review and bibliometric analysis. We did not consider other factors such as the population of a country, etc. that may affect the results and analysis in this study.

Although electrochemical technologies can encourage modular water treatment, there are several obstacles to overcome and factors to consider, such as capital evaluation. PEC electrolysis was conducted utilizing a diverse range of nanomaterials, including nanotubes, nanowires, nanorods, semiconductor nanosheets, and graphene-based materials. Tuning the energy band gap levels may change the electrical characteristics of nanomaterials. Due to a lack of acceptable candidate materials or stability constraints under severe reaction conditions, the obtained efficiencies of water-splitting using semiconductor-based photoelectrochemical cells have been lower than those required in a practical device. The total PEC cell efficiency for water splitting is still relatively low; thus, it is necessary to increase the efficiency and practicality of the photo-water splitting system, notably by developing high-efficiency and cost-effective materials. The unique features of nanomaterials open up many possibilities for constructing high-photocatalytic efficiency water-splitting devices that use sunlight. Tuning the energy band gap levels may change the electrical characteristics of nanomaterials. Using nanomaterials in semiconductors lowers the band gap, allowing more solar light to be absorbed. The least frequent keywords mean the lack of research in those areas such as “cathode”, “glucose”, “silicon photoanodes”, “cuprous-oxide”, “sentization”, “solvothermal synthesis”, “H₂S”, “electrolytes”, “n-type gan”. These topics are needed to be considered in the future investigation of PEC water splitting and hydrogen production. Finally, this research led to a better understanding of the existing use and difficulties of the PEC and hydrogen by offering recommendations for future research, such as improving photoanodes for solar water splitting. These enhancements to the PEC would make it a simple scientific and practical instrument for clean hydrogen generation sustainability management.

Concluding remarks

In the previous 30 years, this bibliometric investigation found an increasing trend in published publications and relative research interest connected to many disciplines. Bibliometric analyses of photoelectrochemical (PEC) water splitting and hydrogen production are crucial for linking research needs within a global technology landscape and, as demonstrated here, provide a comprehensive overview of scientific output over time and its potential future impact. The present study's goal was to undertake a bibliometric examination of two title search keywords, “photoelectrochemical” and “hydrogen”, along with a state-of-the-art overview to bring up systematic analysis and new possibilities in these domains. The work delivered a systematic structural image and traced the effects of the PEC and hydrogen topic. In this work, we have explored VOSviewer and RStudio, publicly accessible computer tools for creating and viewing bibliometric maps and developing research and countries. As a result, 936 papers from 1970 to 2022 were examined using the WoS database. The world

annual growth rate and trends of publications and citations in PEC and hydrogen research have been steadily growing. In order to investigate the connections between authors and the countries where papers on PEC and hydrogen were produced, a co-authorship analysis of both authors and countries was undertaken. Remarkably, the number of articles expanded dramatically between 2007 and 2021, with documents from the USA, China, Korea, Japan, and India leading the scientific output on this discipline. As the flagship journal of the field, the *International Journal of Hydrogen Energy* published most articles. We also realized that the three most productive researchers are Ibrahim Dincer, followed by Yong Li, and Sahab Dass. Co-authorship analysis may also be performed on journals to see how the social structure generated by them has changed over time and assess and rank the field. The author's productivity and relationship analysis shows that most clusters are mainly from Chinese organizations and comprise several most productive scholars. The network co-occurrence analysis showed that “efficient”, “TiO₂”, “evolution”, “visible-light”, and “generation” nodes have the subsequent largest size signifying concepts that have the highest keywords incidences. The future research hotspot in this field may include “cathode”, “glucose”, “silicon photoanodes”, “cuprous-oxide”, “sentization”, “solvothermal synthesis”, “H₂S”, “electrolytes”, “n type gan”.

Author contributions

W. Nabgan, A.H.K. Owgi and B. Nabgan design the bibliometric data; A.A. Jalil, I. Hussain, T.V. Tran, and M. Alhassan performed and collect data; W. Nabgan, and M. Ikram wrote the original draft preparation; MB Bahari, F. Medina, A.H. Nordin and L. Parashuram review and edit the paper. The published version of the manuscript has been read and approved by all authors.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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