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CONFERENCE REPORT

Photosynthesis and hydrogen energy for sustainability: harnessing the sun for a greener future

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Abstract

At the dawn of the 21st century, the rapid expansion of manufacturing plants and the widespread destruction of natural habitats significantly contributed to accelerating global warming. This phenomenon has led to severe droughts, irreversible agricultural damage, and substantial challenges in securing food supplies for the burgeoning global population. The alarming surge in atmospheric carbon dioxide concentrations underscores the urgent need to embrace clean energy technologies. To date, the primary goal of mankind is to develop innovative approaches to return Earth's ecology to its pre-industrial condition, as a century ago. The special issue (SI) in the International Journal of Hydrogen Energy presents a collection of papers on photosynthetic and biomimetic hydrogen (H_2) production, presented at the 'Photosynthesis and Hydrogen Energy Research for Sustainability – 2023' conference, held in Istanbul, Turkey, from 3–9 July 2023 (https://phrs-conference.com). The event was supported by the International Society of Photosynthesis Research (ISPR) and the International Association for Hydrogen Energy (IAHE). SI aims to deliver the latest insights into sustainable energy, with a particular emphasis on Biohydrogen and Artificial Photosynthesis. At the conference, nine promising young investigators were honoured with awards. Included herein are photographs capturing the conference's congenial atmosphere. We cordially invite you to the 12th International Meeting of 'Photosynthesis and Hydrogen Energy Research for Sustainability – 2024', honouring esteemed researchers John Allen (UK), Eva-Mari Aro (Finland), Ibrahim Dincer (Canada), Kazunari Domen (Japan), Elizabeth Gantt (USA), Andrey Rubin (Russia), and scheduled to take place in Turkey (13–19 October 2024).

Keywords: artificial photosynthesis; hydrogen production; international conference; photosynthesis.

Highlights

- Research in artificial and natural photosynthesis
- Hydrogen production from microalgae and cyanobacteria
- Photosynthesis and Hydrogen Energy Research for Sustainability – 2023

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Abbreviations: AI – artificial intelligence; CV – cyclic voltammetry; EV – electric vehicle; ETC – electron transport chain; FTIR – Fourier transform infrared; GHG – greenhouse gas; GNS – graphene nanosheet; GQDs – graphene quantum dots; H_2ase – hydrogenase; N_2ase – nitrogenase; OER – O_2 evolution reaction; ORR – O_2 reduction reaction; PBR – photobioreactor; PV – photovoltaic; RS – Raman spectroscopy; SI – special issue; TEM – transmission electron microscopy; VIPV – vehicle-integrated photovoltaic; XRD – X-ray diffraction.

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Introduction

Photosynthesis, a key process defining the metabolic specificity of phototrophic organisms (higher plants and green algae), takes place within specialised organelles called 'chloroplasts'. Chlorophyll (Chl) *a* and *b* pigments, involved in photosynthesis, capture light energy. Then this captured energy, stored as nicotinamide-adenine dinucleotide phosphate (NADPH) and adenosine triphosphate (ATP), fuels the 'dark' processes, including the Calvin cycle, for carbon dioxide (CO_2) fixation and glucose synthesis. The photosynthetic electron transport chain (ETC) relies on water (H_2O) as its primary electron donor, undergoing oxidation in an oxygen (O_2)-evolving complex. The main pathway, known as linear electron flow, moves electrons through the chain 'H_2O – $NADP^+$ – Calvin cycle' (Allakhverdiev *et al.* 2010, Allakhverdiev 2012, Lawrence *et al.* 2023). Electron transport involves three key pigment–protein complexes: photosystem I (PSI), photosystem II (PSII), and cytochrome b_6/f (cyt b_6/f), all located in the chloroplast's thylakoid membrane. Mobile electron carriers, such as plastoquinones, plastocyanin, and ferredoxin, are crucial for the interactions between these complexes. Furthermore, the accumulation of protons in the thylakoid membrane's lumen creates an electrochemical gradient. This gradient generates a proton-motive force essential for the phosphorylation of adenosine diphosphate (ADP) to ATP, carried out by the chloroplast ATP synthase, a complex protein structure in the thylakoid membrane. The combined activities of the photosynthetic ETC and chloroplast ATP synthase are termed photophosphorylation (Allakhverdiev *et al.* 2010, Lawrence *et al.* 2023).

The emergence of artificial photosynthesis is particularly intriguing, representing an innovative approach of mimicking the natural photosynthetic process found in plants to harness solar energy for sustainable fuel production. Artificial photosynthesis involves the creation of photoelectrochemical cells, often called 'artificial leaves', designed to emulate the complex mechanisms of natural photosynthesis. These cells employ semiconductor materials to capture sunlight and initiate water splitting, thereby generating electrons. These electrons then drive chemical reactions that synthesise valuable fuels or chemicals (Najafpour *et al.* 2015, 2022; Kamshybayeva *et al.* 2023). The overarching aim is to produce a clean, renewable energy source, while also addressing climate change by converting CO_2 into value-added products. Despite considerable advancements, there are ongoing challenges including efficiency optimisation and scaling up for practical applications. Hence, addressing these challenges is vital for the realisation of artificial photosynthesis as a viable and sustainable energy solution (Kossalbayev *et al.* 2024).

In recent years, alternative energy sources have gained traction leading to the introduction of new terms, such as biodiesel, biohydrogen (bio-H_2), biobutanol, bioethanol, biooil, and biogas (Kamshybayeva *et al.* 2024a). A key area of scientific research is the exploration of sustainable raw materials crucial for biofuel production, especially focusing on the biophotolysis-based H_2 production process. Among various bioenergy industries, H_2 production is recognised as one of the most ecologically benign yet technologically demanding, presenting significant potential to tackle a range of upcoming challenges. However, about 50% of the world's H_2 energy is produced through coal reformation, while only a tiny fraction, around 0.1%, is biologically synthesised (Sandybayeva *et al.* 2022). Despite intensive research efforts, this gap persists as no effective biological producer for authentic bio-H_2 synthesis has been identified to date. Therefore, the potential of different biological organisms for H_2 production is subject to keen investigations. In this context, cyanobacteria have shown promising results, demonstrating their capability for molecular H_2 separation through biophotolysis (Yu *et al.* 2022).

Phototrophic microorganisms form a diverse group widely distributed across natural ecosystems, thriving in environments from freshwater to oceans, representing a remarkable breadth of biodiversity (Akimbekov *et al.* 2023, Balouch *et al.* 2023, Sadvakasova *et al.* 2023a, Bauenova *et al.* 2024, Kamshybayeva *et al.* 2024b). Their ability to harness sunlight utilising photosynthetic pigments enables them to drive essential cellular processes, such as O_2 generation, nitrogen (N_2) fixation, and secondary metabolites production, making these microorganisms indispensable in biotechnological applications (Hess *et al.* 2016, Sadvakasova *et al.* 2023b). In the prospect of global sustainability, cellular enzymatic activity shows great potential in tackling various challenges, particularly in the production of bio-H_2. Two key enzymes, nitrogenase (N_2ase) and hydrogenase (H_2ase) play central roles in this context. N_2ase is involved in both N_2 fixation and ATP generation, demanding a significant amount of energy, especially under stressful conditions (Zayadan *et al.* 2018, Xiao *et al.* 2019, Akimbekov *et al.* 2021, Le and Kim 2021). H_2ase, on the other hand, operates in anaerobic conditions within vegetative cells, facilitating the release of H_2 molecules. Furthermore, N_2ase not only produces H_2 but also effectively fixes atmospheric N_2, enriching the soil. This enzyme converts atmospheric N_2 into ammonia (NH_4) while simultaneously releasing H_2 as a by-product and converting ADP energy into ATP. Meanwhile, H_2ases, a diverse group of H_2-evolving enzymes with varying structures, properties, and functions, catalyse the fundamental chemical reaction of H_2 formation by combining protons and electrons (Mishra *et al.* 2019, Islam *et al.* 2020, Russell *et al.* 2020, Sadvakasova *et al.* 2020).

The integration of microalgae and cyanobacteria biomass with artificial photosynthesis represents a promising frontier in sustainable energy research. Microalgae and cyanobacteria, metabolically adaptable and rich in bioactive compounds, become pivotal players in this synergy, serving as a valuable feedstock for artificial photosynthesis and offering a sustainable and renewable source (Ramakrishnan *et al.* 2023). Due to the capability of harnessing solar energy and fixing atmospheric CO_2, the above microorganisms can be considered an ideal renewable resource for artificial photosynthesis.

Artificial photosynthesis can be employed to produce H_2 gas from water, leveraging the energy harnessed by microalgae and cyanobacteria. Biomass-derived components, rich in photosynthetic pigments and catalysts, act as facilitators in splitting water molecules, thereby releasing H_2 and O_2 (Xie *et al.* 2022). This integrated approach addresses the challenges of both efficient biomass utilisation and sustainable H_2 production while contributing to the broader objective of transitioning towards cleaner energy sources. Thus, refining the synergistic relationship between microalgal or cyanobacterial biomass and artificial photosynthesis holds the promise of unlocking new avenues for efficient, eco-friendly, and scalable H_2 energy production (Parmar *et al.* 2011, Akimbekov *et al.* 2022, Sahu *et al.* 2023).

Commercialising photosynthetic H_2 production faces significant challenges that impede its feasibility and scalability. One of the key challenges is the limited penetration of light into dense cultures, which reduces the efficiency of photosynthesis and, consequently, H_2 production (Li *et al.* 2022, Redding *et al.* 2022, Novoveská *et al.* 2023, Gaurav *et al.* 2024). Moreover, the low activity of H_2ase, responsible for the final step of H_2 production, presents a major bottleneck. Indeed, competing metabolic pathways often prioritise biomass accumulation over H_2 production, further reducing overall yields. To overcome these obstacles, researchers are actively employing various multifaceted strategies. For instance, cultivation conditions are being optimised, focusing on factors such as nutrient availability, temperature, and light intensity to maximise H_2 production (Petrova *et al.* 2020, Chen 2022). Genetic engineering also plays a significant role by modifying microorganisms to increase H_2ase activity and reorient metabolic pathways towards greater H_2 production. Furthermore, innovations in photobioreactor (PBR) design are being pursued to improve mass transfer and ensure more effective light distribution in cultures. Advancements in synthetic biology are contributing to the creation of strains with improved characteristics for superior H_2 production. Thus, the search for measures to solve the above challenges is imperative for the development of cost-effective and scalable commercial photosynthetic H_2 production systems. Indeed, successfully navigating these issues will position microalgae and cyanobacteria as viable renewable sources of clean and sustainable H_2 fuel, marking a significant step in the shift towards greener energy alternatives (Oey *et al.* 2016).

Future perspectives

Nowadays, about 25% of the Earth's electricity consumption is generated from renewable sources, with the remaining 75% still dependent on conventional ones. Within the realm of renewable energy, H_2 stands out as one of the cleanest and highest-quality energy carriers available (Ahmad and Zhang 2020). Despite its relatively low input for overall H_2 production, the biological pathway, particularly involving microalgae and cyanobacteria, is highly promising. Utilising these organisms for H_2 production not only curtails greenhouse gas (GHG) emissions but also significantly contributes to mitigating global warming, thereby elevating the significance of biotechnology in this field.

However, a major impediment to widespread adoption is the economic viability of bio-H_2 production, compounded by the inefficiencies and high costs associated with current storage techniques (Hussain *et al.* 2017). Ongoing research aimed at increasing H_2 yields is largely focused on genetic engineering, specifically targeting gene manipulations. Nevertheless, the success of these metabolic engineering efforts is varied as altering the physiological properties of the organisms can sometimes have unintended, more importantly adverse, consequences, potentially reducing biomass productivity (Beiter *et al.* 2024).

In the quest for genome modification, transcriptomic, genomic, and metabolomic tools came into play to delve into the analytical results and intricacies of cell metabolism (van Ruijven *et al.* 2019). The insights gained from these studies are crucial in developing strains capable of efficient H_2-splitting *via* metabolic engineering. Advancements in artificial intelligence (AI)-based modelling are expected to significantly streamline research processes, aiding in identifying key factors for selecting the most suitable wild-type organisms and optimising H_2 production. The emergence of synthetic biology tools requires these promising AI models to strive to standardise biological processes and yield predictable outcomes (Chae *et al.* 2017). The current state of the research paves the way for commercialising H_2 production by developing high-productivity strategies and well-organised transportation and storage systems to ensure a reliable and secure supply (Montaño López *et al.* 2022).

The future of H_2 production, especially photo-synthetically derived, depends not only on scientific progress but also on a range of economic and societal factors. While advancements in the genetic engineering of microorganisms and the development of advanced PBRs are crucial, the economic aspects, such as the costs of mineral resources, social acceptance, and practical applications of H_2 energy, are equally important (Xu *et al.* 2022). Currently, developed countries like Japan and the USA are pioneering the use of H_2 energy in public transportation systems. However, its broader adoption across different sectors requires making the H_2 production process economically viable (Nnabuife *et al.* 2022). A collaborative effort by both scientists and engineers is requested to establish H_2 energy as a key player in the future energy landscape.

Special Issue overview

We are thrilled to present the Special Issue (SI), which features a selection of outstanding papers from the international conference held in Istanbul, Turkey. This event was a gathering point for a diverse group of researchers, scientists, students, and engineers, all dedicated to exploring the realms of natural and artificial photosynthesis, as well as H_2 energy for sustainability. For this SI, we have curated high-quality research articles in relevant research fields. In the following pages, a comprehensive report summarising the key highlights and discussions from the conference is presented.

Sharma *et al.* (2024) presented a comprehensive investigation of the charged particle dynamics and electrochemical behaviour of $SrTiO_3$-δ, a material known for its cubic perovskite structure, to assess its suitability as an anode material for Intermediate Temperature Solid Oxide Fuel Cells (IT-SOFCs). The authors synthesised $SrTiO_3$-δ using a conventional solid-state reaction method and tested its electrochemical response in various pH environments, including 1 M Na_2SO_4, 1 M KOH, and 0.5 M H_2SO_4 solutions. X-ray diffraction (XRD) measurements confirmed the cubic phase of $SrTiO_3$-δ with a lattice constant (a) of 390.5 nm. The material's electrical properties were characterised by a frequency range of 1 to 10^6 Hz and a temperature span of 25 to 700°C. Jonscher's Power Law and scaling behaviour analyses were applied to understand the charged particle dynamics and conduction mechanism of $SrTiO_3$-δ. Cyclic voltammetry (CV) studies indicated electrocatalytic activity, affirming redox processes in neutral and basic media, as evidenced by X-ray photoelectron spectroscopy. Notably, the interaction between the Ti *d*-orbitals and O *p*-orbitals, observed in the redox coupling, points to the potential of $SrTiO_3$-δ in applications beyond fuel cells, including sensors and other electrochemical devices (Sharma *et al.* 2024).

Sarkar *et al.* (2024) reported on the enhancement of a platinum (Pt)-based graphene nanosheet (Pt/GNS) catalyst through citric acid surface modification. The study involved thorough characterisations using various techniques, including Raman spectroscopy (RS), Fourier transform infrared (FTIR) spectroscopy, thermo-gravimetric analysis, XRD, field emission scanning electron microscopy, and transmission electron microscopy (TEM). The electrocatalytic activity of this modified catalyst for the O_2 reduction reaction (ORR) in an alkaline solution was compared with the performance of platinum on carbon (Pt/C) catalyst. The functionalised Pt/GNS demonstrated superior ORR activity, with a half-wave potential of 0.86 V and an impressive electron transfer rate of 3.9 electrons per O_2 molecule. Moreover, the catalyst maintained remarkable stability even after 10,000 cycles, suggesting its great potential for efficient use in various electrochemical applications (Sarkar *et al.* 2024).

Novel iron (Fe)-based electrocatalysts, including Fe_2Se_3, Fe_2O_3, and Fe_2Se_3/Fe_2O_3 heterostructures, were investigated with a focus on reducing overpotential in the O_2 evolution reaction (OER) (Sohail *et al.* 2024a). Among examined electrocatalysts, the Fe_2Se_3/Fe_2O_3 heterostructure was identified as an exceptionally promising candidate for OER due to its efficiency, cost-effectiveness, and reduced overpotential. This electrocatalyst exhibited outstanding performance metrics, with an onset potential of 1.31 V and a low overpotential of only 160 mV at a current density of 20 mA cm^{-2}, thereby outperforming the benchmark Fe-based OER catalysts. Furthermore, the Fe_2Se_3/Fe_2O_3 heterostructure maintained a stable current density of 65 mA cm^{-2} during controlled potential electrolysis at 1.65 V, demonstrating its electrochemical robustness. Remarkably, the method of hydrothermal synthesis used is relatively simple, enhancing their applicability in water-splitting applications.

Sohail *et al.* (2024b) explored the potential of novel CoSe/CoO heterostructures as efficient catalysts for the OER, a key process in clean H_2 production through water electrolysis. The significance of electrocatalysts in accelerating OER kinetics is well-recognised, and cobalt (Co)-based materials, particularly noted for their low overpotential and cost-effectiveness, have gained traction in this context. CoSe/CoO heterostructures were synthesised using hydrothermal methods and demonstrated outstanding electrochemical performance: low onset potential of 1.31 V and overpotential of a mere 170 mV at a current density of 40 mA cm^{-2} for OER. This performance surpassed the existing benchmark Co-based catalysts. Furthermore, during controlled potential electrolysis at 1.65 V, the heterostructure exhibited remarkable stability, maintaining a consistent current density of 60 mA cm^{-2}.

Bhosale *et al.* (2024) addressed the critical need for efficient electrocatalysts in industrial electrochemical water splitting, focusing on reducing energy barriers in both H_2 and O_2 evolution reactions. The study explored the enhancement of vanadium oxide (V_2O_5) electrocatalysis by integrating it with reduced graphene oxide (rGO) and nickel oxide (NiO) nanostructures for water oxidation. The developed VrG/NiO electrocatalyst, characterised by a flower-like V_2O_5-NiO structure on rGO, showed remarkable OER performance. The optimised VrG/NiO ratio demonstrated superior efficiency with minimal overpotential and a low Tafel slope in 1 M KOH solution. Electrocatalyst stability was confirmed after 5,000 CV cycles and 15 h of chronopotentiometry, indicating its durability. A key achievement of the VrG/NiO electrocatalyst was attaining a low cell voltage for overall water splitting which can be attributed to its substantial electrochemical active surface area, redox capability, and synergistic effects (Bhosale *et al.* 2024).

Kesarwani *et al.* (2024) successfully synthesised graphene quantum dots (GQDs) using an eco-friendly microwave-assisted technique and explored their role in enhancing H_2 storage in magnesium hydride (MgH_2). Various characterisation techniques, including TEM, ultraviolet-visible (UV-vis) spectroscopy, RS, FTIR, and XRD, were employed to analyse the GQDs, which were found to range from 3 to 10 nm in size. Exploring the de/re-hydrogenation kinetics of MgH_2 mixed with varied concentrations of GQDs, a significant improvement was observed at 7 wt% GQDs. The onset dehydrogenation temperature for MgH_2 was substantially lower (300°C), representing a 60°C reduction compared to the same sample without GQDs under identical conditions. Additionally, the MgH_2 displayed rapid H_2 reabsorption, highlighting its catalytic efficacy. It was also found that the GQD-catalysed MgH_2 exhibited robust cyclic stability in re-hydrogenation, maintaining its H_2 storage capacity even after 25 cycles.

Thus, the success of the above non-precious metal electrocatalysts paves the way for new practical OER applications, while offering valuable insights into developing efficient non-noble metal-based electrocatalysts for the electrochemical water-splitting process.

Broussos *et al.* (2024) achieved an enhanced H_2 production using the *Synechococcus elongatus* PCC7942 PAMCOD strain, applying a refined method. Glycogen breakdown, induced by N_2 depletion, led to an extraordinary increase in H_2 evolution – up to 10,000-fold. Meanwhile, the structural integrity of phycobilisome remained preserved. The process's sustainability was confirmed *via* the maintained viability of cyanobacterial biomass post-dark fermentation, with the cells showing the ability to proliferate in both double and N_2-enriched BG-11 media. Study findings indicate a significant advancement in H_2 production, with the identification of endogenous glycogen-derived glucose as the primary carbon source for fermentation.

Parlak *et al.* (2024) explored the enhancement of electric vehicle (EV) battery life by integrating solar photovoltaic (PV) and fuel cell technologies. The study focused on the role of vehicle-integrated photovoltaic (VIPV) systems in extending the driving range of EVs, utilising *TRNSYS* and *MATLAB* software to analyse solar radiation and assess vehicle dynamics, particularly exploring the placement of PV panels on vehicle's exterior surfaces. A key aspect of the study was identifying the optimal positioning of PV panels, taking into account tilt and azimuth angles, as well as energy capture efficiency. Different types of PV panels were examined across European locations, considering geographical and seasonal fluctuations in solar radiation. Furthermore, battery longevity was investigated by examining current amplitude and fluctuations based on the Worldwide Harmonised Light Vehicles Test Cycle. The proposed topology indicated that the integration of VIPVs enhanced battery current amplitude and fluctuations by 7.3 and 5.3%, respectively (Parlak *et al.* 2024).

Akimbekov *et al.* (2024) discussed hydrogenotrophic methanogenesis within coal-bearing environments, focusing on energy production, C sequestration, and H_2 availability. Methane, a valuable energy source and a potent GHG, is primarily produced through hydrogenotrophy by methanogenic archaea. This process, pivotal for C cycling and H_2 storage, gains significance in coal, abundant in complex organic matter. The review highlights the knowledge gaps relative to the origins of coalbed methane and the microbial communities involved, particularly the hydrogenotrophic methanogens (Akimbekov *et al.* 2024). Detailed insights into hydrogenotrophic methanogens in coal beds and similar environments were provided delving into energy production mechanisms, unique metabolic pathways, and ecological functions (Akimbekov *et al.* 2024).

Transitioning from a broad overview to a more focused analysis, the challenges and opportunities in advancing H_2 energy development in Turkey, in the context of the targets set by the government in 2023, have been thoroughly reviewed (Yilmaz *et al.* 2024). The article critically evaluated several key factors, including research and development efforts, government strategy, economic benefits, and production technologies. A SWOT analysis offering an in-depth look at Turkey's current H_2 energy landscape was presented as well. The analysis underscored the necessity of overcoming existing challenges and increasing investments in both research and infrastructure to support the expansion of the H_2 economy in Turkey. It was concluded that the advancement of green H_2 energy is crucial for Turkey, not only to enhance its energy security and reduce environmental impact but also to meet international climate commitments, thereby strengthening Turkey's position in the global energy market (Yilmaz *et al.* 2024).

SaberiKamarposhti *et al.* (2024) examined the integration of H_2 energy and AI within smart grid systems, specifically the potential of AI technologies to be utilised for optimising energy processes, improving grid resilience, and facilitating predictive maintenance. The review acknowledged the challenges that accompany these technological advancements, notably data privacy concerns and the necessity for standardised communication protocols. In addition, the study highlighted the importance of ongoing research to overcome technical barriers in AI-driven grid management. Indeed, autonomous energy management systems, the application of edge AI, and decentralisation were identified as key elements for increasing grid adaptability. The need for policy considerations, such as implementing data privacy regulations and modernising grid policies, to ensure the security of power grids was emphasised. Furthermore, the authors advocate for reforms in the energy market and the adoption of technology-neutral approaches to foster renewable energy practices. The strategic vision presented in the article aims to establish a flexible, efficient, and environmentally conscious energy future by integrating H_2 energy into smart infrastructures using AI.

The conference

The 11th International Photosynthesis Conference on Hydrogen Energy Research and Sustainability 2023 was organized in honour of Robert Blankenship, Győző Garab, Michael Grätzel, Norman Hüner, and Gunnar Öquist, in Istanbul, Turkey at Bahçeşehir University Future Campus from 3–9 July 2023. The conference saw active participation from 150 attendees representing 31 countries. These countries included Australia, Austria, Azerbaijan, Belarus, Bulgaria, Canada, China, Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, India, Iran, Israel, Italy, Japan, Jordan, Kazakhstan, Korea, Latvia, Mongolia, Nepal, New Zealand, Pakistan, Poland, Romania, Russia, Singapore, Slovakia, Spain, Sweden, Switzerland, Syria, Tajikistan, Turkey, The Netherlands, UK, Ukraine, and USA.

The conference, held from 3–9 July 2023, provided a platform for participants to engage in discussions spanning the past, present, and future of photosynthesis research. The topics covered a wide spectrum, ranging from molecular-level insights to global aspects of this vital biological process. For more information about

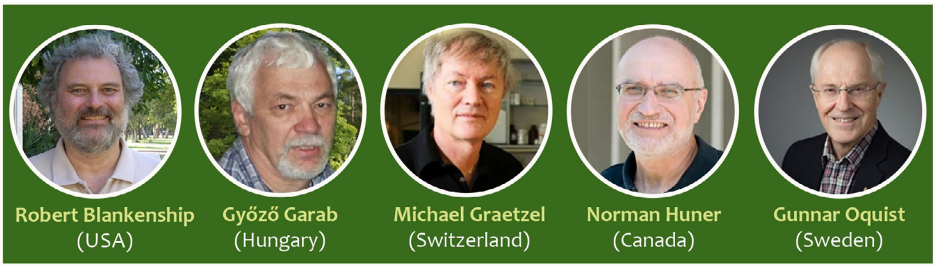

Fig. 1. Honorary persons of the international conference. Photos courtesy by owners.

the conference, you can visit the official website at https://past.phrs-conference.com.

Julian J. Eaton-Rye from New Zealand served as the conference chairman, with Barry Bruce from the USA as the co-chairman. Tatsuya Tomo from Japan held the position of Secretary for the International Committee, and Girayhan Yilmaz chaired the local organizing committee. The coordination of this meeting was overseen by Suleyman I. Allakhverdiev.

There were over 40 speakers, listed alphabetically: Agepati S. Raghavendra, Anjana Jajoo, Anna Frank, Arvi Freiberg, Barry Bruce, Bekzhan Kossalbayev, Bolatkhan Zayadan, Cristopher Gisriel, Dmitry Dunikov, Francesco Francia, Gergely Nagy, Gunnar Öquist, Győző Garab, İbrahim Dinçer, Iftach Yacoby, Irada Huseynova, Ismail Zulfugarov, Jan Kern, Keisuke Kawakami, Kentaro Ifuku, Kostas Stamatakis, Lorenzo Ferroni, Mahdi Najafpour, Marc Nowaczyk, Marek Živčák, Maria Borisova-Mubarakshina, Michael Graetzel, Milan Szabo, Mohammad Yusuf Zamal, Natalia N. Rudenko, Norm Huner, Ondřej Dlouhý, Rajagopal Subramanyam, Robert Blankenship, Stefano Santabarbara, Suleyman Allakhverdiev, Tatsuya Tomo, Thomas D. Sharkey, Václav Karlický, Vasily V. Ptushenko, Yoshifumi Ueno, Yutaka Shibata. In addition, we had about 50 posters.

Fig. 1 depicts the ‘Honorary Persons at International Conference’, featuring images of distinguished academicians and scholars. Figs. 2, 3, and 4 are dedicated to showcasing both individual and group participants of the conference, highlighting contributions and interactions. Fig. 5 captures young scientists, recognised for outstanding work, receiving their well-deserved awards. The scientific program of the conference was both comprehensive and engaging, encompassing a wide range of topics related to photosynthesis research. The event was especially valuable for international students, postdoctoral researchers, and emerging scientists, providing them with ample opportunities to deepen their knowledge of photosynthesis.

The conference thoroughly addressed various critical aspects of photosynthesis, placing them within a broader global context, including H_2 production and artificial photosynthesis. The discussions covered a wide array of topics, such as the functionalities of Type I and Type II reaction centres; details of photosynthetic ETC and photophosphorylation; complex mechanisms of water oxidation; dynamics of light absorption; intricacies of C_3, C_4, and CAM photosynthesis; regulatory mechanisms controlling photosynthetic gene expression; formation and development of the photosynthetic apparatus; interactions between photosynthesis and various environmental stress factors; recent advancements in artificial photosynthesis; exploration of photosynthesis and biomimetic methods in H_2 production; role in enhancing crop yields and biomass productivity; educational approaches for teaching;

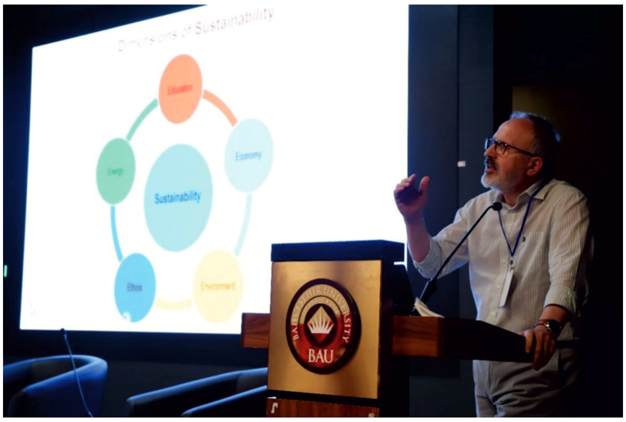

Fig. 2. Professor Ibrahim Dincer, a world-renowned expert in clean energy, delivering a presentation on Green Technology. Photo by Girayhan Yilmaz, Turkey.

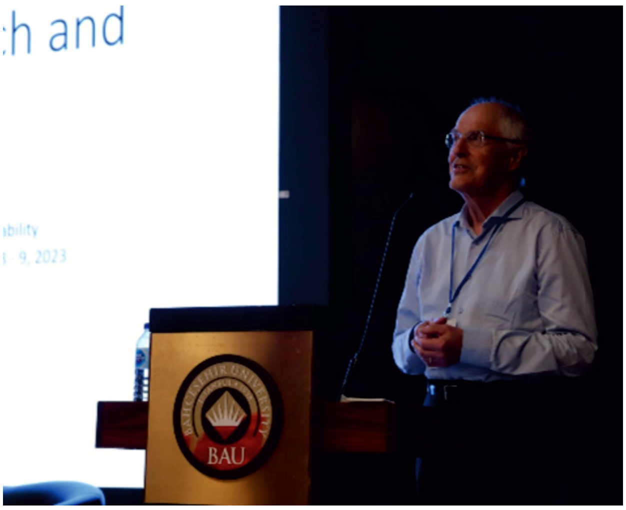

Fig. 3. Photo of Prof. Gunnar Öquist. Photo by Girayhan Yilmaz, Turkey.

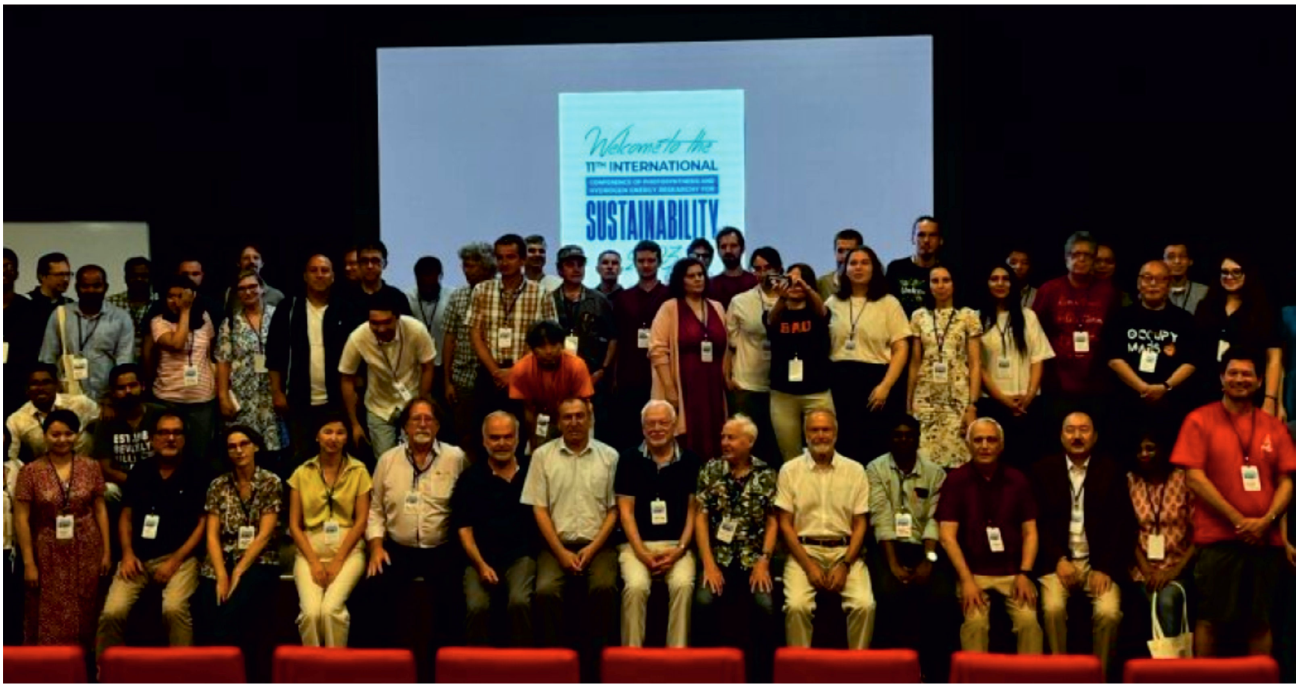

Fig. 4. Group photo of the participants taken after the opening of the conference. Photo by Girayhan Yilmaz, Turkey.

Fig. 5. Winners of the young researcher awards (*front row*), *from left*: Avratanu Biswas (Hungary), Kinga Ilona Böde (Hungary), Daria Vilyanen (Russia), Elena Zadneprovskaya (Russia), Sabit Mohammad Aslam (Hungary), and Pavithra Ramachandran (India). Some of the selection committee members and organizers are also in the second row, *from left*: Suleyman Allakhverdiev, Tom Sharkey, Francesco Francia, Győző Garab, Stefano Santabarbara, Tatsuya Tomo, and Rajagopal Subramanyam. Photo by Girayhan Yilmaz, Turkey.

the application of bioinformatics for understanding photosynthetic processes.

The conference underscored the interdisciplinary nature of photosynthesis research, highlighting its connection to global challenges and cutting-edge technological innovations. By encompassing a variety of thematic areas, the event showcased the pivotal role of photosynthesis, from the molecular details of photosynthetic reactions to its practical implications in enhancing crop productivity and developing renewable energy sources. Key discussions at the conference emphasised the importance of advancing educational resources and computational tools to deepen knowledge. Thus, the conference served as a convergence of diverse ideas and perspectives, fostering a holistic understanding of photosynthesis and its multifaceted impacts not only on natural ecosystems but also on various human endeavours.

Young researchers at the conference

The Photosynthesis Conference served as an exceptional platform for acknowledging the outstanding contributions of young researchers in the realm of 'Photosynthesis and Hydrogen Energy Research for Sustainability'. Six outstanding individuals, including Ph.D. students and postdoctoral scholars, were honoured at this event, highlighting their remarkable dedication and innovative contributions to advancing the field. The selection process was rigorous, with conference organisers meticulously reviewing numerous presentations and research projects submitted by highly talented participants. The chosen awardees demonstrated not only a commitment to advancing photosynthesis research but also the ability to present their findings with clarity and impact.

Each of the six young researchers was honoured with a well-deserved cash prize of 100 USD, acknowledging their exceptional achievements in the field. Among these awardees, one was specifically selected for outstanding poster presentation, covering a range of themes, reflecting the wide spectrum of research in photosynthesis and H_2 energy. The poster session was a significant aspect of the conference, offering young researchers a dynamic platform to showcase their findings and engage in meaningful discussions with fellow scientists. Poster sessions encouraged the exchange of ideas, allowed for valuable feedback, and fostered potential collaborations with experts in the field. For students and post-doctoral researchers, this interactive environment proved invaluable, presenting a unique opportunity to learn from and interact directly with eminent scientists in the global Photosynthesis and Hydrogen Energy community.

The conference prominently highlighted the importance of nurturing and supporting young talent in the scientific community. Thus, recognising the outstanding achievements of young researchers aimed to encourage continued dedication and innovation in H_2 energy and photosynthesis research. The awardees served as inspiring examples for their peers, encouraging others to strive for excellence in their scientific pursuits. Moreover, the event reinforced the essential role of photosynthesis and H_2 energy research in tackling sustainability challenges, specifically in mitigating climate change and driving forward a sustainable future for our planet.

The awards ceremony was a celebration of the significant contributions these young researchers have made to the broader scientific community. It underscored the importance of their research in advancing photosynthesis research and its potential applications in sustainability.

Awarded young scientists at the conference:

(*1*) Avratanu Biswas (Hungary) – 'Modelling of energy transfer from phycobilisomes to PSI in the cyanobacterium *Synechocystis* sp. PCC6803';

(*2*) Kinga Ilona Böde (Hungary) – 'Evidence for the role of isotropic lipid phase in the fusion of PSII membranes';

(*3*) Sabit Mohammad Aslam (Hungary) – 'Differences in the heat susceptibility and involvement of NDH-2 in alternative electron transport in coral endosymbiont algae, *Symbiodiniaceae*';

(*4*) Pavithra Ramachandran (India) – 'Photosynthetic efficiency and transcriptome analysis of *Dunaliella salina* under hypersaline conditions: a retrograde signaling mechanism in the chloroplast';

(*5*) Daria V. Vilyanen (Russia) – 'New insights into the inhibitory activity of dinitrophenol ether of iodonitrothymol and the functional properties of the cytochrome b_6/f complex';

(*6*) Elena V. Zadneprovskaya (Russia) – 'Biotechnological potential of the green microalgae *Coelastrella* sp. IPPAS H-626'.

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