Laidlaw Foundation Report 1

Literature Review - Hydrogen in the modern world

Hydrogen is currently under heightened interest globally due to its potential as a clean and sustainable fuel replacement for fossil fuels. As of now, global demand for hydrogen is approaching 80 Mt per annum, with the hydrogen generation market projected to be worth 201 billion by 2025, up from 143 billion in 2019 – this represents a forecasted CAGR of 9.2%. The number of policies focused on hydrogen development is increasing accordingly, with many countries aiming to take advantage of large-scale production and decreasing renewable energy costs to produce green hydrogen at a comparable price to its fossil fuel-generated counterpart.

In particular, the Asia Pacific region is playing a significant role in the green hydrogen market. Japan and South Korea are notable for their investments into hydrogen fuel cells since 2009, with particular emphasis on their use in residential areas and automobiles. China, Singapore, India, and Malaysia are all starting or expected to launch policies backing hydrogen fuel and its large-scale generation.

For example, Japan is one of the world's leading nations in hydrogen development, being one of the first countries to implement a hydrogen strategy focusing on reducing production cost and promoting international hydrogen trade. From 2017 to 2019 alone, the government doubled its hydrogen-related research budget to 300 million and has plans to supply 10% of energy generation power from hydrogen by 2050. In the automotive industry, Japan has additional goals of 200,000 green hydrogen-based vehicles by 2025 to meet global carbon emission standards. One of the most notable recent developments is the Fukushima Hydrogen Energy Research Field, a 10MW-class (the largest in the world) hydrogen production facility powered by renewable energy and launched in 2020 to produce hydrogen by electrolysis for use in fuel cells.

Given the recent interest in hydrogen research and development, generation of hydrogen through photocatalysis is increasingly under research due to its clean and sustainable nature. Photocatalysis utilizes the energy absorbed from light to drive reactions in a photosynthesis-inspired process: in semiconducting photocatalysts, water splitting is carried out through the creation of electron-hole pairs from the promotion of electrons between the conduction band and valence band on the catalyst. The charge separation due to photon absorption drives water reduction and oxidation in surface reactions on the catalyst, producing H_2 and O_2. A method for hydrogen generation based primarily on solar power has the potential to revolutionize the energy system.

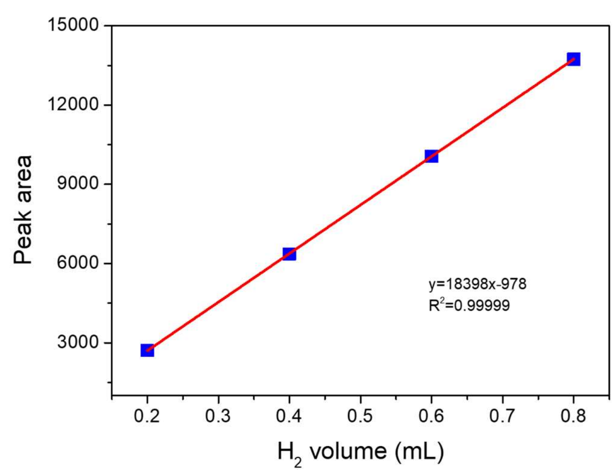
The research project mainly focuses on the use of ruthenium to enhance the photocatalytic properties of graphitic carbon-nitride. Ruthenium acts as a cocatalyst: in this case, it can promote the hydrogen evolution reaction ($2H^+ + 2e^- \rightarrow H_2$) on the surface of the catalyst. The process of adding supplementary materials to facilitate electron movement and promote higher activity in photocatalysts is crucial to increasing efficiency and thus viability of a catalyst, in some cases causing a hydrogen generation rate orders of magnitude above the base catalyst. The optimization of this material ratio allows for further comparison of the different deposition zones of cocatalysts on g-C_3N_4, and further research can be carried out to determine a suitable OEC configuration to potentially create a commercially viable photocatalyst.

Methodology

Ru_xP/CN and Ru_xP@CN (surface and bulk combination respectively) is synthesized for use in the photocatalytic reactor and subject to tests under the following conditions.

Activity test

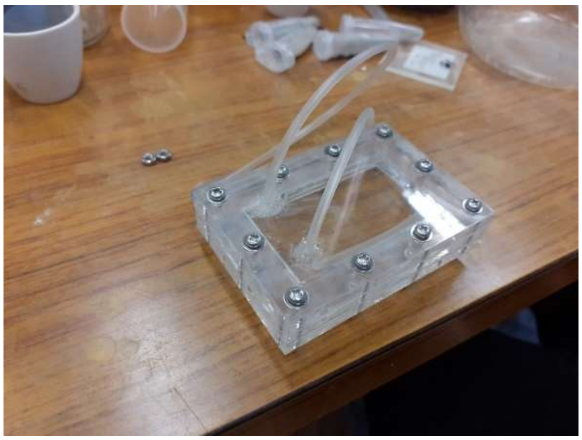
A standard curve is constructed for the peak area of H_2 gas from 0.5 to 2.5 ml. Extrapolation of the data points suggested a line of $y = 18398x - 978$ for the experimental reactor, with an R^2 value of over 0.9999. This allowed for performance comparison of the different ratios of Ru_xP.



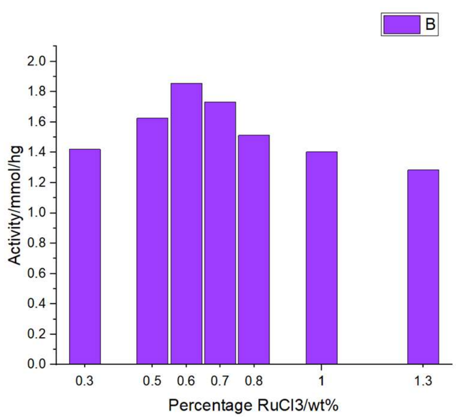
A simple reactor fabricated from PMMA is used to carry out the experiment as seen in the accompanying image. A 25x25mm PMMA plate with a 20x20mm engraving for catalyst deposition acts as the main reaction locus.

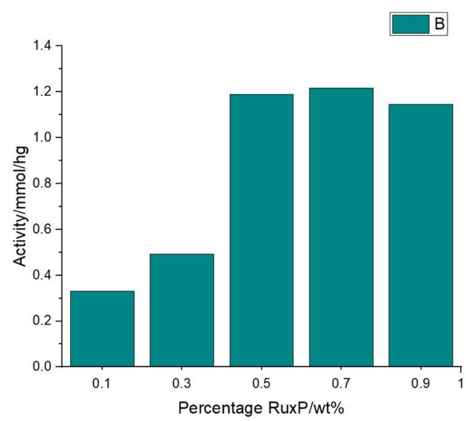
10 mg of solid is mixed with 100 µl of ethanol and 10 µl of $C_7HF_{13}O_5S \cdot C_2F_4$ (Nafion), then briefly sonicated. 50 µl of this solution is then deposited onto the PMMA plate and dried. 3.5 ml of vol 10% $C_6H_{15}NO_3$ (Triethanolamine) is added to the reactor with the plate inside.

The system is purged with argon for 10 minutes, after which the reactor is subject to artificial light conditions for 30 minutes at room temperature. The amount of H_2 evolved after this period is measured through gas chromatography and comparison with the standard curve.



Results





An optimal ratio of bulk and surface incorporation of Ru_xP/CN was found, as seen in the above graphs, indicating a maximum hydrogen production rate of 1.85 $mmolh^{-1}g^{-1}$ at a 0.6 wt % $RuCl_3$ ratio and 0.6 wt % Ru_xP respectively. Additionally, it was found that the use of ruthenium cocatalysts create a photocatalyst that exhibits increased performance under alkaline conditions, increasing threefold from original activity under extreme conditions. These findings exhibit significantly increased hydrogen production through the use of a ruthenium phosphide cocatalyst, and the optimization of this catalyst opens an avenue for further research into its properties and performance. Investigation into the mechanisms and detailed structure of the synthesized compounds is in progress, and it is hopeful that a much better understanding will be achieved in the near future.

Development of leadership skills

Personal growth in leadership skills has been a theme throughout the project's course. As seen through the above project work, a great deal of analysis and research has been carried out, with a focus on improving communication skills – particularly in receiving information and digesting it. Time management in an environment that necessitates efficiency and organization to meet appropriate deadlines challenged and developed overall coordination skills, while communicating regarding necessary resources and discussing results with various individuals has helped to develop my social aptitude.

Although the findings here are limited by both time and resource constraints, they are built on solid theory and offer a glimpse into future innovations in creating a world backed by green energy. This work will be part of an ongoing process to research original materials for hydrogen generation and will hopefully form the basis for future publication.

The qualities developed throughout this period are particularly relevant in the scientific community, in which there is a great wealth of knowledge to digest and incorporate in order to produce meaningful and useful work. The importance of communication and cooperation on a global scale in the technological sector cannot be understated, and it is only through the shared intelligence of academic minds across the planet that we can achieve true progress.