# From Sunlight to Clean Hydrogen:

## A Qatar–Oman Research Collaboration Advancing Sustainable Energy

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The global energy demand continues to grow rapidly as populations expand and economies develop. At the same time, concerns about climate change and environmental sustainability are pushing governments, industries, and researchers to rethink how energy is produced. Fossil fuels such as coal, oil, and natural gas have powered modern society for more than a century, but their environmental impact has become increasingly clear. As a result, the search for cleaner and more sustainable energy alternatives has become one of the most important scientific challenges of our time.

Among the many renewable energy solutions currently under investigation, hydrogen has emerged as one of the most promising candidates for the future energy system. Hydrogen is often referred to as a clean fuel because the only by-product produced during its use in fuel cells or combustion systems is water. In addition, hydrogen has a very high energy density, meaning it can store and deliver large amounts of energy efficiently. These characteristics make hydrogen particularly attractive for applications ranging from transportation to electricity generation and energy storage.

Despite these advantages, the production of hydrogen remains a significant challenge. Today, most hydrogen is produced using fossil fuel-based

methods such as steam methane reforming, which releases large amounts of carbon dioxide. To fully realize hydrogen's potential as a clean energy carrier, scientists must develop new technologies capable of producing hydrogen in environmentally friendly ways. One of the most promising approaches is solar-driven photocatalysis, a process that uses sunlight and specialized materials to split water molecules into hydrogen and oxygen.

Photocatalysis relies on materials known as photocatalysts, which absorb light and use its energy to trigger chemical reactions (Figure 1). When sunlight strikes a photocatalyst, electrons within the material become excited and move to higher energy states. These excited electrons can then participate in chemical reactions that split water molecules and produce hydrogen gas. Because this process uses sunlight as the energy source and water as the raw material, it offers a highly sustainable pathway for hydrogen production.

Carbon-based nanomaterials have attracted significant attention in energy and environmental research due to their unique electrical, optical, and catalytic properties. These materials can be classified according to their dimensional structure, including zero-dimensional (0D), one-dimensional (1D), and two-dimensional (2D) nanostructures. As illustrated in Figure 2, examples of these materials include carbon dots and fullerenes (0D), carbon nanotubes and carbon nanofibers (1D), and graphene and graphitic carbon nitride (2D). Each class of nanomaterials exhibits distinct structural characteristics that influence how electrons move through the material and how efficiently light energy can be utilized in photocatalytic reactions. Because of these properties, carbon nanomaterials are widely explored for applications in solar energy conversion, hydrogen production, sensing, and environmental remediation.

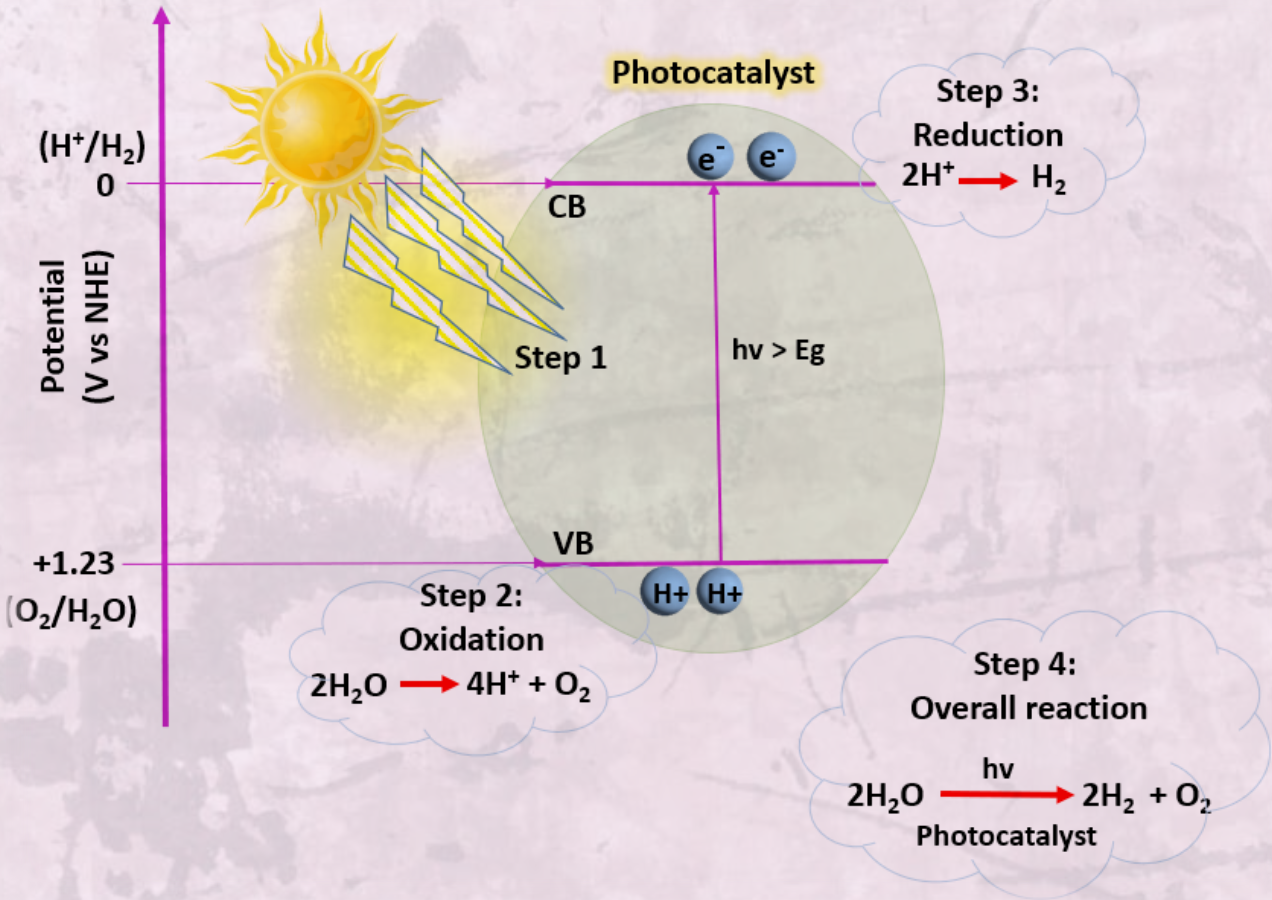



**Figure 1:** Schematic diagram showing the mechanism of hydrogen production using photocatalytic water splitting.

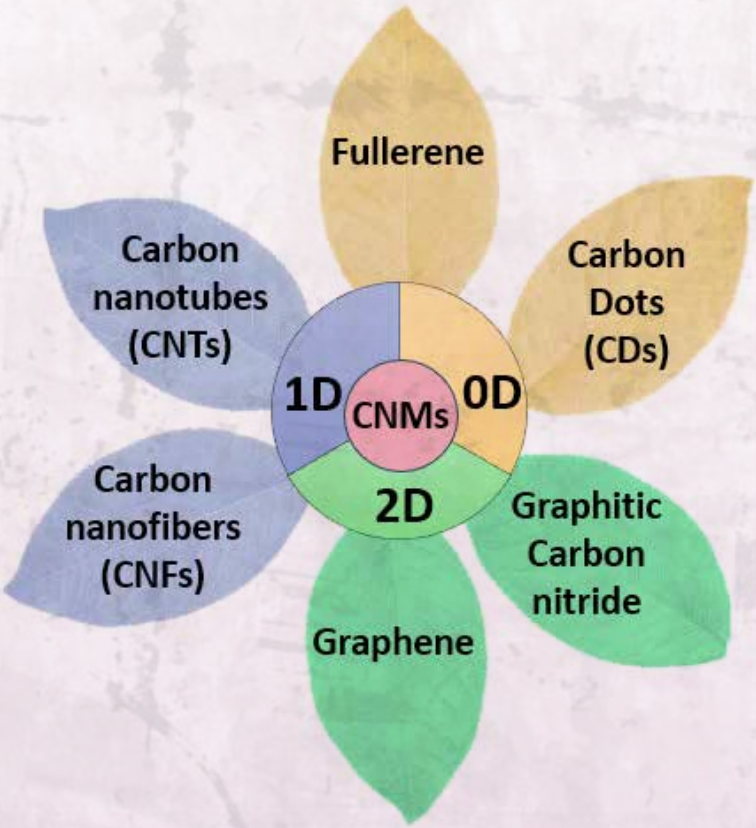



**Figure 2:** Dimensional classification of carbon nanomaterials.

However, designing photocatalysts that are both efficient and stable remains a major scientific challenge. Many conventional photocatalysts either absorb only a small portion of the solar spectrum or experience rapid recombination of electrons and holes before the chemical reaction can occur. Overcoming these limitations requires the development of new materials and innovative strategies for improving light absorption and charge transfer.

In this context, researchers from Qatar University and Sultan Qaboos University in Oman collaborated on a research project aimed at developing advanced photocatalytic materials for hydrogen production. The project was supported by the Qatar University Internal Research Collaboration Grant (IRCC), which promotes scientific cooperation between Qatar University and international research partners. By combining expertise in materials science, nanotechnology, and chemical engineering, the research team sought to design a photocatalyst capable of efficiently producing hydrogen using natural sunlight.

The study focused on combining two well-known semiconductor materials: titanium dioxide ($TiO_2$) and graphitic carbon nitride ($g\text{-}C_3N_4$). Titanium dioxide is one of the most widely used photocatalysts because it is chemically stable, inexpensive, and environmentally friendly. However, it mainly absorbs ultraviolet light, which represents only a small fraction of sunlight that reaches the Earth's surface. Graphitic carbon nitride, on the other hand, can absorb visible light more effectively but suffers from rapid recombination of charge carriers, which reduces its catalytic efficiency.

To address these limitations, the researchers engineered a hybrid structure known as a heterojunction, in which nanoscale particles of titanium dioxide are anchored onto thin layers of graphitic carbon nitride. This design allows the two materials to work together in a complementary way. When sunlight excites electrons within the photocatalyst, the heterojunction structure promotes efficient movement of these electrons between the two materials, reducing energy losses and enhancing the photocatalytic reaction.

An additional innovation in the research was the use of a green synthesis approach for producing the titanium dioxide nanoparticles. Instead of using conventional chemical additives, the researchers employed a natural plant extract derived from Moringa leaves as a template during the synthesis process (Figure 3). This environmentally friendly method not only reduces the use of potentially harmful chemicals but also helps control the size and distribution of the nanoparticles, improving the overall performance of the photocatalyst.

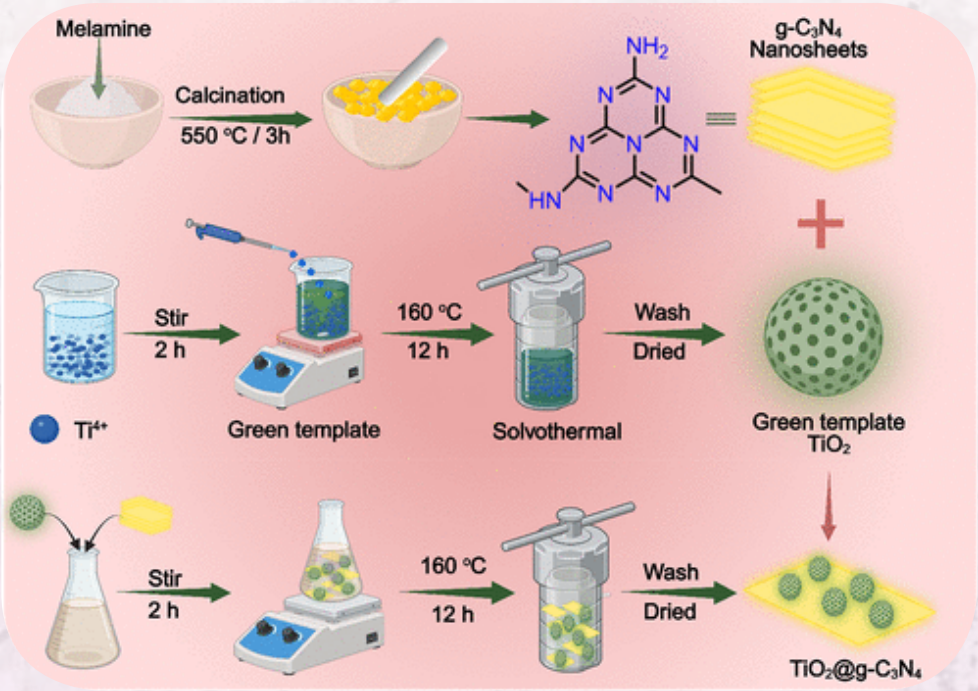



**Figure 3:** Schematic Illustration of the Synthesis of (g-$C_3N_4$), (Green $TiO_2$), and $TiO_2$@g-$C_3N_4$ Nanoheterojunction Photocatalysts.

The newly developed material was tested under natural sunlight to evaluate its ability to produce hydrogen. The results demonstrated a significant improvement compared with the individual materials used alone. The hybrid $TiO_2$@g-$C_3N_4$ photocatalyst produced hydrogen at a rate far higher than that achieved by either titanium dioxide or graphitic carbon nitride individually. This improvement is attributed to the strong interaction between the two materials, which enhances light absorption and facilitates efficient separation of photogenerated charges.

Another important aspect of the research is the stability of the photocatalyst. For practical energy applications, catalytic materials must maintain their performance over repeated reaction cycles. The experiments showed that the $TiO_2$@g-$C_3N_4$ heterostructure remains stable during multiple hydrogen production cycles, demonstrating its potential for long-term use in solar hydrogen generation systems.

Beyond the scientific findings, this project highlights the importance of international collaboration in advancing sustainable technologies. The partnership between Qatar University and Sultan Qaboos University brought together complementary expertise and resources, enabling the team to tackle complex research challenges and develop innovative solutions. Such collaborations are essential for addressing global issues such as climate change and energy sustainability.

The research also reflects Qatar University's broader commitment to supporting cutting-edge research that contributes to global sustainability goals. By investing in innovative energy technologies and fostering collaboration with international partners, the university plays an important role in advancing scientific knowledge and developing solutions for the energy challenges of the future.

Looking ahead, further research will focus on improving the efficiency of photocatalytic materials and scaling up these technologies for real-world applications. While significant challenges remain, advances in materials science and nanotechnology continue to bring the vision of solar-driven hydrogen production closer to reality.

Harnessing sunlight to produce clean hydrogen fuel represents a powerful opportunity to transform the global energy landscape. Through continued innovation and collaboration, research initiatives such as this one are helping pave the way toward a more sustainable and environmentally responsible energy future.