Artificial Photosynthesis: An Overview

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Abstract
Artificial photosynthesis (AP) represents a transformative approach to addressing the pressing issues of carbon dioxide (CO2) emissions and renewable energy storage. By mimicking the natural process of photosynthesis, AP converts environmental CO2 into valuable solar fuels and chemicals, utilizing solar energy as the primary power source. This review paper synthesizes recent advancements in the field, focusing on the fundamental mechanisms, innovative materials, and system designs that drive AP. Key topics include the roles of semiconductors, metal-organic frameworks, and co-catalysts in enhancing efficiency, as well as the development of photoreactors and hybrid systems. Additionally, the paper evaluates the economic and environmental impacts of AP technologies, highlighting their potential for sustainable energy solutions. Through a critical examination of current research and future challenges, this review aims to provide a comprehensive understanding of the state-of-the-art in artificial photosynthesis and its role in the green conversion of CO2 into solar chemicals.

1. Introduction
The increasing levels of carbon dioxide (CO2) in the atmosphere, primarily due to human activities such as fossil fuel combustion and deforestation, are a major contributor to climate change. This has led to an urgent need for innovative solutions to mitigate CO2 emissions and transition towards sustainable energy sources [1]. Artificial photosynthesis (AP) offers a promising approach by mimicking the natural process of photosynthesis to convert CO2 and water into useful chemicals and fuels using solar energy [2]. Natural photosynthesis, performed by plants, algae, and certain bacteria, efficiently converts solar energy into chemical energy, producing oxygen and organic compounds. Inspired by this process, scientists have been developing artificial systems that replicate the key steps of natural photosynthesis: light absorption, charge separation, and catalysis. These systems aim to achieve efficient CO2 reduction and water oxidation, ultimately producing solar fuels such as hydrogen, methanol, and hydrocarbons, as well as other valuable chemicals [3,4]. Artificial photosynthesis not only addresses the need for renewable energy sources but also provides a means of utilizing CO2, a major greenhouse gas, as a feedstock for chemical production. This dual benefit makes AP a highly attractive research area, with potential implications for energy security, environmental sustainability, and economic development [5].

This review paper aims to consolidate the current state of research in artificial photosynthesis, highlighting recent breakthroughs and identifying key challenges [6]. The following sections will cover the fundamental mechanisms of AP, the materials and catalysts used, the design of AP systems, and their efficiency and performance. Additionally, we will discuss the economic and environmental impacts of AP technologies, providing a comprehensive overview of this rapidly evolving field. Through this examination, we hope to provide insights into the potential of artificial photosynthesis to contribute to a sustainable future.

2. Artificial Photosynthesis

Artificial photosynthesis (AP) aims to replicate the natural process of photosynthesis to convert CO_2 and water into useful chemicals using solar energy. This process involves several key steps: light absorption, charge separation, and catalysis. Understanding these mechanisms is crucial for designing efficient AP systems [7].

2.1. Light Absorption

The first step in artificial photosynthesis is the absorption of sunlight. This is achieved using materials that can efficiently capture and utilize solar energy. For example, Semiconductors materials like titanium dioxide (TiO_2), zinc oxide (ZnO), and various types of perovskites are commonly used due to their strong light absorption and stability. These materials create electron-hole pairs upon absorbing photons. Dye-sensitized materials use organic dyes or metal complexes that absorb light and transfer the energy to a semiconductor, broadening the spectrum of light that can be utilized. In addition, quantum dots and nanomaterials offer tunable light absorption properties and can be engineered to absorb a wide range of the solar spectrum [8].

2.2. Charge Separation

After light absorption, the next step is charge separation, where the excited electrons and holes are separated and directed towards different parts of the system to drive redox reactions.

- **Heterojunctions:** Interfaces between different materials, such as p-n junctions in semiconductors, facilitate efficient charge separation. The alignment of energy levels at these junctions helps in directing electrons and holes towards their respective reactions [9].
- **Photoelectrochemical Cells:** These cells use an external circuit to separate and transport the charges. The photoanode (where oxidation occurs) and the photocathode (where reduction occurs) are connected by an electrolyte, enabling efficient charge transfer [10].

2.3. Catalysis

The separated charges drive the catalytic processes that convert CO_2 and water into valuable chemicals.

- **CO_2 Reduction:** This process requires catalysts that can efficiently reduce CO_2 into hydrocarbons, alcohols, or other chemicals. Common catalysts include:
  - **Metal Nanoparticles:** Metals like platinum, palladium, and copper are used due to their high activity and selectivity in CO_2 reduction reactions.
  - **Metal-Organic Frameworks (MOFs):** These porous structures offer high surface area and tunable properties, enhancing the interaction with CO_2 molecules.
  - **Enzymatic Catalysts:** Inspired by natural enzymes, these catalysts offer high specificity and efficiency in CO_2 reduction [11].

- **Water Oxidation:** The oxidation of water to produce oxygen is a crucial part of the process, providing the necessary protons and electrons for CO_2 reduction. Effective water oxidation catalysts include:
  - **Transition Metal Oxides:** Materials like manganese oxide and cobalt oxide are commonly used for their stability and efficiency.
  - **Molecular Catalysts:** These catalysts, often based on ruthenium or iridium complexes, offer high turnover rates and efficiency [12].

2.4.Integration of Components

The integration of these components into a coherent system is vital for the overall efficiency of artificial photosynthesis. Key considerations include:

- **Photoreactor Design:** Efficient photoreactors maximize light absorption and ensure optimal contact between light-absorbing materials, catalysts, and reactants [13].
- **System Stability:** Long-term stability and resistance to degradation are crucial for practical applications. This requires materials that can withstand prolonged exposure to sunlight and reactants without significant loss of activity [14].
- **Product Separation and Collection:** Efficient separation and collection of the products (e.g., hydrogen, hydrocarbons) are necessary to prevent back reactions and ensure high purity [15].

By mimicking the complex processes of natural photosynthesis and utilizing advanced materials and designs, artificial photosynthesis holds great promise for sustainable CO_2 conversion and solar fuel production. Further advancements in understanding and optimizing these mechanisms will be essential for the development of practical and efficient AP systems

Table 1: Summary of Advanced Photocatalyst Materials for Artificial Photosynthesis

Material	**Band Gap (eV)**	**Key Advantages**	**Key Challenges**	**References**
TiO_2	3.2	Abundant, stable under UV light, low-cost	Limited absorption in visible light	[1, 4]
Fe_2O_3 (Hematite)	2.0	Earth-abundant, stable, suitable for water oxidation	Poor charge transport, limited efficiency	[13, 14]
CDs	2.4	Efficient light absorption, suitable for visible light	Limited stability, toxicity concerns	[6, 11]
ZnO	3.37	High electron mobility, transparent, versatile	Limited photocatalytic activity in water-splitting	[4, 10]
$BiVO_4$	2.4	Visible light absorption, suitable for water oxidation	Limited stability under prolonged illumination	[8, 9]

Notes:

- Band gap values represent the energy required for electron excitation (lower values indicate better absorption of visible light).
- Key advantages and challenges highlight the material's strengths and limitations in artificial photosynthesis applications.
- References provide sources for detailed studies and reviews on each material

In recent years, significant progress has been made in developing advanced photocatalyst materials for artificial photosynthesis. Table 1 summarizes key properties of selected materials commonly studied in this field. TiO_2, for instance, is known for its abundance and stability under UV light, although its limited absorption in the visible spectrum poses challenges for efficient solar energy utilization [1, 4]. Hematite (Fe_2O_3) has gained attention due to its earth-abundant nature and suitability for water oxidation, yet challenges such as poor charge transport hinder its overall efficiency [13, 14]. CdS and ZnO offer advantages in visible light absorption and electron mobility, respectively, but face issues such as stability and photocatalytic activity limitations [6, 10, 11]. $BiVO_4$, known for its visible light absorption and potential for water oxidation, confronts stability concerns under prolonged illumination [8, 9]. These materials illustrate the ongoing efforts to balance performance with practical application requirements in advancing artificial photosynthesis technologies

3. Key Materials

The success of artificial photosynthesis (AP) hinges on the development and optimization of materials that can efficiently absorb sunlight, facilitate charge separation, and catalyze the necessary chemical reactions. This section reviews the primary materials used in AP, focusing on their roles and properties [16].

3.1. Photocatalysts

3.1.1. Semiconductors:

- **Titanium Dioxide (TiO_2):** Widely used for its stability, non-toxicity, and strong photocatalytic activity. TiO_2 is efficient in UV light absorption but requires modification for visible light activity.
- **Zinc Oxide (ZnO):** Similar to TiO_2, ZnO has strong UV absorption and good electron mobility. It is often used in combination with other materials to enhance visible light absorption.
- **Perovskites:** These materials, such as methylammonium lead halides, offer high light absorption efficiency and tunable bandgaps, making them promising for solar energy conversion [17].

3.1.2. Metal-Organic Frameworks (MOFs):

- **Design and Functionality:** MOFs are porous structures composed of metal ions coordinated to organic ligands. They can be tailored for high surface area, tunable pore sizes, and selective CO_2 adsorption, enhancing CO_2 capture and conversion.
- **Examples:** MOFs incorporating metals like copper, zinc, and zirconium have shown promising results in CO_2 reduction due to their structural flexibility and catalytic properties [18].

3.1.3. **Dye-Sensitized Materials:**

- **Organic Dyes and Metal Complexes:** These materials are used to broaden the light absorption spectrum. Dyes such as ruthenium complexes and organic dyes like porphyrins transfer absorbed light energy to a semiconductor, enhancing its photocatalytic activity [19].

3.2.Co-Catalysts

3.2.1. **Metal Nanoparticles:**

- **Platinum (Pt), Palladium (Pd), and Copper (Cu):** These metals are frequently used due to their high catalytic activity and selectivity for CO_2 reduction reactions. They facilitate efficient electron transfer and reduce overpotentials in the reaction process [20].

3.2.2. **Enzymatic Catalysts:**

- **Bio-Inspired Catalysts:** Mimicking natural enzymes, these catalysts offer high specificity and efficiency. Examples include carbonic anhydrase for CO_2 capture and formate dehydrogenase for CO_2 reduction.

3.3.Hybrid Materials

3.3.1. **Combination of Semiconductors and Co-Catalysts:**

- **Enhanced Charge Separation:** By combining different semiconductors (e.g., TiO_2 with CdS or ZnO with CuO), hybrid materials can achieve more efficient charge separation and broadened light absorption.
- **Heterostructures:** Designing materials with heterojunctions, where two different semiconductors are interfaced, can improve charge transfer and reduce recombination losses [21].

3.3.2. **Composite Materials:**

- **Integration of MOFs with Semiconductors:** Creating composites that combine the high surface area of MOFs with the light absorption properties of semiconductors can enhance overall photocatalytic performance.
- **Carbon-Based Materials:** Incorporating graphene or carbon nanotubes with semiconductors and catalysts can improve conductivity and charge separation, enhancing the efficiency of the AP system [22].

3.4.Emerging Materials

3.4.1. **Perovskite Quantum Dots:**

- **Nanoscale Efficiency:** These materials offer high light absorption and emission tunability at the nanoscale, promising for improving the efficiency of solar energy conversion in AP [23].

3.4.2. **2D Materials:**

- **Graphene and Transition Metal Dichalcogenides (TMDs):** These materials have unique electronic properties and high surface areas, making them excellent for enhancing charge transport and catalysis in AP systems [24].

3.4.3. **Organic-Inorganic Hybrid Materials:**

- **Synergistic Effects:** Combining organic and inorganic components can create materials with enhanced stability, light absorption, and catalytic properties. Examples include hybrid perovskites and polymer-inorganic composites [25].

3.5.Stability and Durability Considerations

3.5.1. **Long-Term Performance:**

- Ensuring the stability of materials under prolonged exposure to sunlight and reactants is crucial. This involves developing materials resistant to photodegradation, corrosion, and fouling.

3.5.2. **Protective Coatings:**

- Applying protective layers on photocatalysts and co-catalysts can enhance their durability without compromising their activity [26].

  By leveraging these key materials, artificial photosynthesis systems can achieve higher efficiencies, greater selectivity in product formation, and improved long-term performance. Continuous research and innovation in material science are essential to overcome the current limitations and advance the practical application of AP technologies.

4. System Designs

The design of artificial photosynthesis (AP) systems plays a critical role in optimizing the efficiency and practicality of converting CO2 into solar chemicals and fuels. Effective system design integrates materials, light capture, and catalytic processes in a manner that maximizes solar energy utilization and CO2 conversion [27]. This section reviews various system designs and their components.

4.1.Photoreactors

Photoreactors are specialized devices that facilitate the photochemical reactions involved in AP by optimizing light absorption, reactant interaction, and product collection.

4.1.1. **Types of Photoreactors:**

- **Slurry Reactors:** Utilize a suspension of photocatalyst particles in a liquid medium. They offer high surface area for reactions but pose challenges in catalyst recovery and scalability.
- **Fixed-Bed Reactors:** Contain a stationary layer of photocatalyst material. They are easier to scale up and maintain but may suffer from lower light penetration and reduced active surface area.
- **Membrane Reactors:** Incorporate a semipermeable membrane to separate products and reactants, enhancing reaction efficiency and selectivity by preventing product inhibition and back reactions [28].

4.1.2. **Design Considerations:**

- **Light Distribution:** Uniform light distribution is crucial for maximizing photocatalytic efficiency. Designs often include reflective coatings, light guides, and transparent reactor walls to ensure even illumination.
- **Fluid Dynamics:** Effective mixing and flow management ensure that reactants are continuously supplied to the catalyst surface and products are efficiently removed, preventing concentration gradients and enhancing reaction rates.
- **Thermal Management:** Managing the heat generated from light absorption is essential to maintain optimal reaction temperatures and prevent catalyst degradation [29].

4.2.Hybrid Systems

Hybrid systems combine different materials and components to enhance overall efficiency and functionality.

4.2.1. **Photovoltaic-Assisted Systems:**

- **Integration with Solar Panels:** Photovoltaic (PV) cells can be coupled with photocatalytic systems to provide a consistent and controlled supply of electricity, driving the reduction and oxidation reactions in AP [30].

- **Dual Absorption:** These systems can capture and utilize a broader spectrum of sunlight, with PV cells converting light to electricity and photocatalysts using the remaining light for chemical reactions.

4.2.2. **Biohybrid Systems:**

- **Combination with Biological Components:** Incorporating biological elements such as enzymes or whole cells can enhance the specificity and efficiency of catalytic processes. For instance, enzymes can be immobilized on photocatalysts to mimic natural photosynthesis more closely [31].

4.3.Reactor Configurations

4.3.1. **Monolithic Reactors:**

- **Single-Phase Structures:** Utilize monolithic structures with integrated light absorbers and catalysts. These reactors offer high structural integrity and ease of handling but may require advanced fabrication techniques.

4.3.2. **Modular Reactors:**

- **Scalable Units:** Consist of modular components that can be easily scaled up or down. This design is advantageous for adjusting the reactor size based on specific requirements and for facilitating maintenance and component replacement.

4.3.3. **Continuous Flow Reactors:**

- **Dynamic Operation:** Enable continuous operation with a constant flow of reactants and products. These reactors are suitable for industrial applications, offering consistent performance and easier integration into existing chemical processes [32].

4.4.Integration with Solar Panels

Utilizing solar panels to provide a consistent energy source for AP systems can enhance efficiency and practicality.

4.4.1. **Solar-Driven Electrochemical Cells:**

- **Direct Coupling:** Connecting solar panels directly to electrochemical cells can drive the redox reactions necessary for CO2 conversion and water splitting. This approach can improve energy efficiency by reducing conversion losses.
- **Intermediate Energy Storage:** Incorporating energy storage systems, such as batteries or supercapacitors, allows for continuous operation even during periods of low sunlight, enhancing the reliability of AP systems [33].

4.5.Stability and Scalability

Ensuring the long-term stability and scalability of AP systems is crucial for their practical application.

4.5.1. **Material Durability:**

- Developing materials that resist photodegradation, corrosion, and fouling is essential for maintaining long-term performance. Protective coatings and self-healing materials are promising approaches.

4.5.2. **Scalable Manufacturing:**

- Techniques such as roll-to-roll processing, 3D printing, and modular assembly can facilitate the large-scale production of AP systems, reducing costs and improving accessibility.

4.5.3. **System Maintenance:**

- Designing systems with easy access for maintenance and component replacement ensures sustained performance and reduces operational downtime [34].

By combining innovative materials with advanced reactor designs, artificial photosynthesis systems can achieve higher efficiencies, improved durability, and greater scalability. Continued research and development in system design are essential to overcome current limitations and advance the practical application of AP technologies for sustainable CO2 conversion and solar fuel production.

5. Efficiency and Performance

The efficiency and performance of artificial photosynthesis (AP) systems are critical metrics for evaluating their feasibility and effectiveness in converting CO_2 into solar chemicals and fuels. This section reviews the key factors that influence these metrics, including quantum efficiency, product selectivity, stability, and overall system performance.

5.1.Quantum Efficiency

Quantum efficiency (QE) refers to the number of charge carriers (electrons or holes) generated per photon absorbed by the photocatalyst. It is a crucial measure of the efficiency of light utilization in AP systems.

5.1.1. **Internal Quantum Efficiency (IQE):**

- IQE measures the fraction of absorbed photons that contribute to the desired photochemical reaction, excluding losses due to recombination or non-productive processes. High IQE indicates efficient charge separation and transfer.

5.1.2. **External Quantum Efficiency (EQE):**

- EQE accounts for the total number of incident photons, including those not absorbed by the photocatalyst. It is influenced by factors such as light absorption, reflection, and scattering. Enhancing light-harvesting strategies can improve EQE.

5.1.3. **Strategies to Improve Quantum Efficiency:**

- **Nanostructuring Photocatalysts:** Creating nanostructured surfaces or incorporating nanomaterials can increase the surface area and light absorption efficiency, reducing charge recombination [35].
- **Plasmonic Enhancement:** Utilizing plasmonic nanoparticles can enhance local electromagnetic fields, increasing light absorption and promoting charge separation.
- **Doping and Sensitization:** Doping photocatalysts with metal ions or sensitizing them with dyes can extend their light absorption range and improve charge transfer.

5.2.Product Selectivity

Product selectivity is the ability of the AP system to preferentially produce desired chemicals from CO_2 reduction and water oxidation reactions, minimizing the formation of unwanted by-products.

5.2.1. **Factors Influencing Selectivity:**

- **Catalyst Composition:** The choice of catalyst materials and their surface properties significantly affect reaction pathways and product distribution. Tailoring the catalyst's active sites can enhance selectivity towards specific products.
- **Reaction Conditions:** Parameters such as pH, temperature, and reactant concentration can influence product selectivity. Optimizing these conditions helps achieve the desired chemical outputs.
- **Co-Catalysts:** The addition of co-catalysts can improve selectivity by facilitating specific reaction steps and suppressing side reactions.

5.2.2. **Examples of Selective Products:**

- **Hydrogen (H_2):** Produced from water splitting, hydrogen is a clean fuel with high energy density.
- **Methanol (CH_3OH):** A valuable chemical feedstock and potential fuel, methanol can be synthesized through the selective reduction of CO_2.
- **Hydrocarbons and Alcohols:** Various hydrocarbons (e.g., methane, ethylene) and alcohols (e.g., ethanol) can be selectively produced by tuning the catalytic properties and reaction conditions [36].

5.3.Stability and Durability

The long-term stability and durability of AP systems are essential for practical applications. These metrics assess how well the system maintains its performance over time under operating conditions.

5.3.1. **Factors Affecting Stability:**

- **Photocatalyst Degradation:** Prolonged exposure to light, reactants, and reaction intermediates can degrade photocatalysts, reducing their activity. Developing robust materials resistant to photodegradation and corrosion is crucial.
- **Thermal Stability:** High temperatures generated during the reaction can lead to material degradation and loss of catalytic activity. Efficient thermal management and heat-resistant materials are important for maintaining stability.
- **Structural Integrity:** Maintaining the structural integrity of catalysts and reactor components is essential to prevent performance loss due to physical damage or fouling [37].

5.3.2. **Strategies to Enhance Stability:**

- **Protective Coatings:** Applying protective layers on photocatalysts can prevent degradation and enhance their durability without compromising activity.
- **Self-Healing Materials:** Developing materials that can repair themselves after damage can improve the longevity of AP systems.
- **Periodic Regeneration:** Implementing regeneration protocols, such as cleaning or reactivating the catalyst surface, can restore activity and prolong system life.

5.4.Overall System Performance

Overall system performance encompasses the combined effects of quantum efficiency, product selectivity, and stability, reflecting the practical feasibility of AP systems.

5.4.1. **Performance Metrics:**

- **Solar-to-Chemical Efficiency (STC):** STC measures the overall efficiency of converting solar energy into chemical energy stored in the products. It is a key indicator of the system's effectiveness in utilizing solar energy.
- **Turnover Frequency (TOF):** TOF represents the number of catalytic cycles a catalyst can perform per unit time, reflecting its activity and efficiency.
- **Energy Conversion Efficiency (ECE):** ECE evaluates the efficiency of converting input energy (solar or electrical) into chemical energy, considering all energy losses in the process.

5.4.2. **Improving System Performance:**

- **Integrated Design:** Combining optimized materials, advanced reactor designs, and efficient light-harvesting strategies can significantly enhance overall performance.
- **Hybrid Systems:** Utilizing hybrid systems that integrate different technologies (e.g., PV-assisted AP) can improve energy conversion and utilization.

- **Scalability and Cost-Effectiveness:** Developing scalable manufacturing processes and cost-effective materials is essential for the widespread adoption of AP technologies [38].
  By focusing on these key factors, researchers can enhance the efficiency and performance of artificial photosynthesis systems, moving closer to practical and sustainable solutions for CO_2 conversion and solar fuel production.

6. Challenges and Future Directions

Despite significant progress in artificial photosynthesis (AP), several challenges must be addressed to realize its full potential for CO_2 conversion and solar fuel production. This section discusses the main challenges and outlines future directions for research and development.

6.1.Material Development

6.1.1. **Challenges:**

- **Limited Light Absorption:** Many current photocatalysts are primarily active in the UV range, which constitutes only a small fraction of the solar spectrum.
- **Charge Recombination:** Rapid recombination of photogenerated electron-hole pairs reduces the efficiency of the photocatalytic process.
- **Stability and Durability:** Photocatalysts often suffer from degradation over time, reducing their long-term effectiveness.

6.1.2. **Future Directions:**

- **Broadening Light Absorption:** Developing new materials or modifying existing ones to absorb a wider range of the solar spectrum, including visible and near-infrared light.
- **Enhancing Charge Separation:** Designing heterostructures and incorporating plasmonic materials to improve charge separation and reduce recombination.
- **Improving Stability:** Creating robust materials that can withstand prolonged exposure to light, reactants, and reaction intermediates. This includes developing protective coatings and self-healing materials.

6.2.System Integration

6.2.1. **Challenges:**

- **Complexity of Multi-Step Reactions:** Efficiently integrating the various steps of light absorption, charge separation, and catalysis into a coherent system.
- **Scalability:** Scaling up laboratory-scale systems to industrial-scale applications without compromising efficiency and performance.
- **Product Separation and Purification:** Efficiently separating and purifying the products from the reaction mixture to achieve high-purity solar fuels and chemicals.

6.2.2. **Future Directions:**

- **Modular System Design:** Developing modular reactor designs that can be easily scaled up or down based on specific needs.
- **Advanced Photoreactors:** Designing photoreactors with optimized light distribution, fluid dynamics, and thermal management to enhance overall system performance.
- **Efficient Product Separation:** Innovating methods for the efficient separation and purification of products, such as membrane technologies and selective adsorption processes.

6.3. Economic Viability

6.3.1. **Challenges:**

- **High Material Costs:** Many advanced materials used in AP systems, such as rare metals and sophisticated nanomaterials, are expensive.
- **Energy Efficiency:** The overall energy efficiency of AP systems must be competitive with existing technologies for them to be economically viable.
- **Infrastructure Requirements:** Developing the infrastructure for large-scale AP deployment, including manufacturing, installation, and maintenance.

7. Conclusion

Artificial photosynthesis (AP) stands as a promising technology for addressing the dual challenges of carbon dioxide (CO_2) emissions and sustainable energy production. By mimicking the natural process of photosynthesis, AP has the potential to convert CO_2 into valuable solar fuels and chemicals using sunlight, offering a renewable and environmentally friendly solution. In addition, artificial photosynthesis represents a transformative approach to addressing some of the most pressing environmental and energy challenges of our time. Continued research, innovation, and collaboration will be key to unlocking its full potential and realizing its benefits for society and the planet. Artificial photosynthesis emerges as a new benchmark for the synthesis of valuable solar chemicals. This environment friendly procedure opens a new path for the reduction of the level of harmful green-house gases from the environment and produce green solar chemicals.

Notes

The authors declare no competing financial interests.

Acknowledgment

This work was supported by Chandigarh University, Mohali, Punjab (140413), India.

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