International Journal of
Renewable Energy and its Commercialization
https://chemical.journalspub.info/index.php?journal=JREC

ISSN: 2582-4120
Volume 10, Issue 1, 2024
DOI (Journal): 10.37628/IJREC

Review | IJREC

A Review on Nanotechnology for Catalysis and Solar Energy Conversion

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Abstract

This roadmap on Nanotechnology for Catalysis and Solar Energy Conversion focuses on the application of nanotechnology in addressing the current challenges of energy conversion: 'high efficiency, stability, safety, and the potential for low-cost/scalable manufacturing. Solar-to-fuel conversion involves using nanotechnology to improve the efficiency and effectiveness of converting solar energy into chemical fuels. Solar Water Splitting Nanotechnology is applied to enhance the process of splitting water into hydrogen and oxygen using solar energy. Solar Photovoltaics The roadmap covers various types of solar cells, including dye-sensitized solar cells (DSSCs), perovskite solar cells, and organic photovoltaics, with a focus on improving their efficiency and cost-effectiveness. Bio-Catalysis Nanotechnology is explored for enhancing enzymatic reactions for bio-catalysis, which can be valuable for renewable energy applications. The smart engineering of materials and electrodes at the nanoscale is expected to improve the efficiency of solar-to-fuel conversion. Semiconductor Nanoparticles are discussed to enhance solar energy conversion, particularly in the context of DSSCs. Rapid advancements in perovskite solar cells are mentioned, including new ideas for 2D and 3D hybrid halide perovskites. Multiple Exciton Generation (MEG) from hot carriers, is introduced as a potential way to significantly boost photovoltaic efficiency by exploiting the quantization effects in semiconductor nanostructures like quantum dots, wires, or wells. Nanoscale Characterization Methods recognizes the importance of improving methods for characterizing nanoscale materials. Terahertz spectroscopy is highlighted as an example of a technique that can overcome the challenges associated with nanoscale materials characterization. Computational Science is the Computational frameworks and machine learning methods are emphasized as tools to predict structure-property relationships in materials and devices. An emphasis is placed on organic photovoltaics in this context. The "Electrochemical Leaf" is a concept is introduced as an innovation in electrochemistry and beyond, potentially contributing to advancements in various areas of science and technology. Biohybrid Approaches mentions that efficient and specific enzyme catalysts can be combined with nanomaterials for biohybrid approaches, offering unique possibilities for renewable energy applications. The goal of this research is to advance nanotechnology in catalysis and solar energy conversion to provide significant benefits to society, including more efficient and cost-effective renewable energy solutions.

Keywords: Biocatalysis, Solar cells, Water splitting, Renewables, Photocatalysis.

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Received Date: Feb 08, 2024
Accepted Date: June 09, 2024
Published Date: Aug 13, 2024

Citation Nikita Shantaram Jadhav, Ananya Mallikarjun Hiremath, Tushar Bhanudas Khande, Ganesh N. Gaikwad. Design and Implementation of Circular Polarized Patched Antenna For 5G Applications. International Journal of Telecommunications & Emerging Technologies 2024; 10(1): 1–9p.

Introduction:

In the pursuit of sustainable energy solutions, the integration of nanotechnology emerges as a pivotal innovation. At the nanoscale, typically within dimensions of 1 to 100 nanometers, nanotechnology grants unparalleled mastery over material properties and surfaces, rendering it a fitting solution to confront the pressing challenges in energy conversion—chiefly, the quest for high efficiency, stability, safety, and cost-effectiveness [1]. The global appetite for clean, renewable energy is surging, propelled by the imperative to diminish greenhouse gas emissions and break free from fossil fuel dependence. Solar energy stands as a beacon of hope due to its abundant, replenishable nature. Yet, to fully harness its potential, a paramount need exists to elevate the efficiency of energy conversion processes and engineer sustainable energy storage systems. The profound significance of addressing these challenges in catalysis and solar energy conversion resounds by contributions to sustainability, environmental preservation, heightened energy efficiency, and the broader embrace of clean, budget-friendly energy sources. These endeavors are the cornerstone of a secure, eco-conscious energy future.

Nanotechnology plays a significant role in catalysis and solar energy conversion, contributing to advancements in energy efficiency, environmental sustainability, and the development of cleaner technologies [25]. For the catalysis, (i) increased surface area; as the nanomaterials, such as nanoparticles and nanocatalysts, have a high surface area-to-volume ratio. This property enhances catalytic activity, as more active sites are available for chemical reactions, and (ii) improved reactivity: the unique electronic and structural properties of nanomaterials can enhance the reactivity of catalysts. Size, shape, and composition at the nanoscale can be precisely controlled to optimize catalytic performance. In heterogeneous catalysis, nanomaterials are often used, where the catalyst is in a different phase from the reactants. This facilitates catalyst recovery and recycling, making processes more sustainable.

For the Solar Energy Conversion, Nanotechnology has led to the development of advanced materials for solar cells e.g., Photovoltaics. Nanoscale materials, such as quantum dots and nanowires, have unique optical and electronic properties that can be tailored for efficient light absorption and charge carrier transport. For the photocatalysis, Nanomaterials are used as photocatalysts in solar-driven water splitting and pollutant degradation. Semiconductor nanoparticles, like titanium dioxide (TiO_2) and zinc oxide (ZnO), can harness solar energy to drive chemical reactions [6].

In Thin-Film Solar Cells, Nanotechnology enables the fabrication of thin-film solar cells with reduced material consumption and improved flexibility. Nanomaterials like perovskite nanocrystals have shown promise in thin-film solar cell applications [78].

In Energy Storage, Nanotechnology is also crucial in the development of advanced materials for energy storage devices, such as lithium-ion batteries. Nanostructured materials can enhance the performance, stability, and capacity of batteries [910].

In Nanocarriers for Solar Fuel Production, Nanomaterials are employed as carriers for catalysts in solar fuel production. For instance, nanoparticles can act as carriers for catalysts in the production of hydrogen by splitting water using sunlight. The unique properties of nanomaterials make them suitable for improving the efficiency and sustainability of catalytic processes and solar energy conversion technologies. Researchers continue to explore novel nanomaterials and design strategies to address challenges and unlock new possibilities in these fields. Nanotechnology plays a role in improving the efficiency of converting solar energy into fuel, potentially addressing challenges related to energy storage. In Solar water splitting process, it is using solar energy to split water into hydrogen and oxygen. In Photovoltaics, Nanotechnology can enhance the performance of photovoltaic cells, enabling more efficient conversion of sunlight into electricity. In Bio-catalysis, Nanotechnology is applied in the realm of bio-catalysis, which involves using biological catalysts to drive chemical reactions. This could have implications for sustainable energy production. Colloidal quantum materials and semiconductor nanoparticles, such as colloidal quantum materials and semiconductor nanoparticles, may offer unique properties that can be harnessed for energy-related applications. Nanotechnology plays a role in the rapid advancements observed in perovskite solar cells, which have shown promise as a more cost-effective alternative to traditional solar cells. Multiple exciton generation: This concept involves generating multiple charge carriers (excitons) from a single photon, potentially increasing the efficiency of solar cells. In Nanoscale characterization methods and computational science, Nanotechnology often relies on precise characterization methods and computational simulations to understand and optimize materials at the nanoscale. In Electrochemical Leaf, it refers to a revolutionary idea involving electrochemical processes mimicking the functions of a leaf, possibly for more efficient energy conversion [1112]. In Biohybrid approaches, it may explore the potential of combining biological and nanotechnological elements for energy-related applications. The overall theme suggests that the integration of nanotechnology into various aspects of energy conversion holds great promise for developing more efficient and cost-effective renewable energy solutions, ultimately benefiting both society and the environment. The paper discusses the current state of research in these areas and may propose future directions for exploration and development.

Methods of fabrication of different Photovoltaics:

The realm of solar photovoltaics encompasses diverse types of solar cells, each characterized by unique efficiency and cost-effectiveness attributes. Nanotechnology, as a driving force, has ushered in significant enhancements within this domain. In this context, a comprehensive analysis of three key solar cell types is imperative:

Dye-Sensitized Solar Cells (DSSCs)

DSSCs leverage nanotechnology to enhance light absorption and electron transport, ultimately bolstering their efficiency. The intricate interplay between nanomaterials and sensitizing dyes has paved the way for improved conversion rates and cost-effective production methods (Fig.1).

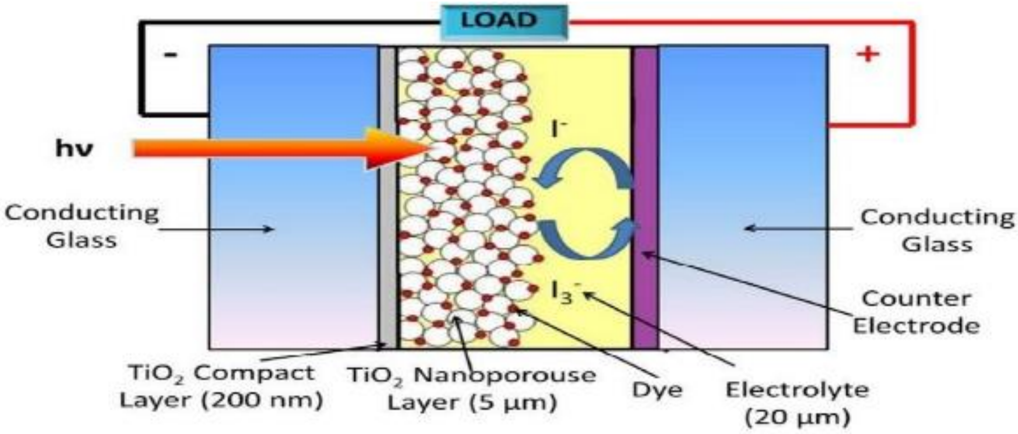

Fig 1: Dye-Sensitized Solar Cells (DSSCs)

Perovskite Solar Cells

Notably, the application of nanotechnology has propelled perovskite solar cells to the forefront of solar energy technology. Through precise control at the nanoscale, researchers have achieved remarkable improvements in efficiency and stability, bolstering the commercial viability of these cells.

Organic Photovoltaics

Nanotechnology has revolutionized the landscape of organic photovoltaics by enabling the engineering of nanostructured materials for enhanced light absorption and charge carrier mobility (Fig 2). Such advancements have resulted in the development of flexible, lightweight, and low-cost solar cell technologies, promising significant contributions to the renewable energy sector. Through an in-depth analysis of these solar cell types, this paper aims to elucidate the pivotal role of nanotechnology in augmenting the efficiency, stability, and cost-effectiveness of solar photovoltaic systems, thereby propelling the transition to a sustainable and economically viable energy landscape.

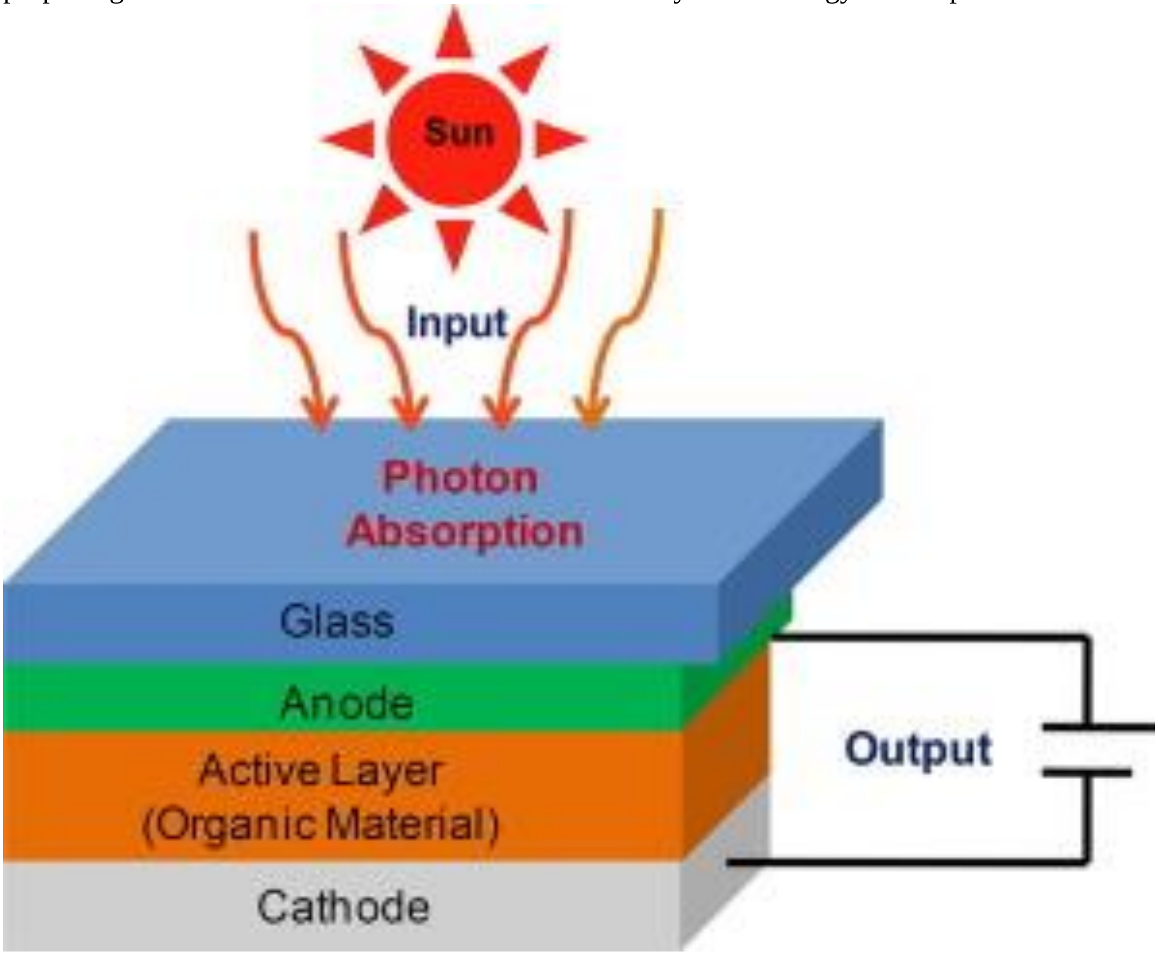

Fig 2: Organic Photovoltaics

Results & Discussions:

Bio-Catalysis and Nanotechnology

Nanotechnology enhances bio-catalysis, improving enzyme efficiency in renewable energy applications. It allows for precise enzyme control and modification at the nanoscale using nanoparticles, nanocarriers, and nanostructured materials. This boosts biofuel production from biomass, waste-to-biogas conversion, and biological fuel cells that generate electricity. Nanoscale adjustments to photosynthetic enzymes hold promise for more efficient biofuel and hydrogen production in artificial photosynthesis.

Solar Water Splitting

Solar water splitting is a promising process that holds the potential to harness solar energy for the production of clean hydrogen fuel. Here, we provide an overview of the solar water splitting process, delve into how nanotechnology enhances its efficiency, and highlight notable advancements and innovations in this field. Solar water splitting is a two-step process that utilizes sunlight to convert water (H2O) into hydrogen (H2) and oxygen (O2). The process involves:

Photocatalysis

Solar energy is used to excite a photocatalyst, typically a semiconductor material, which generates electron-hole pairs. These charge carriers participate in water splitting reactions.

Hydrogen Evolution Reaction (HER)

Electrons produced during photocatalysis reduce protons (H+) from water, forming hydrogen gas (H2).

Oxygen Evolution Reaction (OER)

Holes in the photocatalyst oxidize water to produce oxygen gas (O2). Nanotechnology brings several crucial improvements to the solar water-splitting process

Increased Surface Area

Nanomaterials, such as nanoparticles or nanostructured surfaces, offer a significantly larger surface area for photocatalytic reactions. This enables more efficient light absorption and a higher density of active sites for water splitting.

Tailored Bandgap

Nanoscale engineering allows the precise tuning of the semiconductor's bandgap, optimizing its ability to absorb specific wavelengths of light, thus increasing energy conversion efficiency.

Reduced Charge Carrier Recombination

Nanoscale structures can minimize the recombination of electron-hole pairs, prolonging the lifetime of charge carriers and improving overall photocatalytic efficiency.

Nanotechnology plays a pivotal role in recent solar water-splitting advancements. Stacked semiconductor structures optimize solar spectrum utilization, boosting efficiency (Fig 3.). Cocatalysts accelerate HER and OER reactions. Artificial photosynthesis systems for hydrogen production are gaining traction, with quantum dots offering unique optical properties to enhance photocatalysis in solar water splitting.

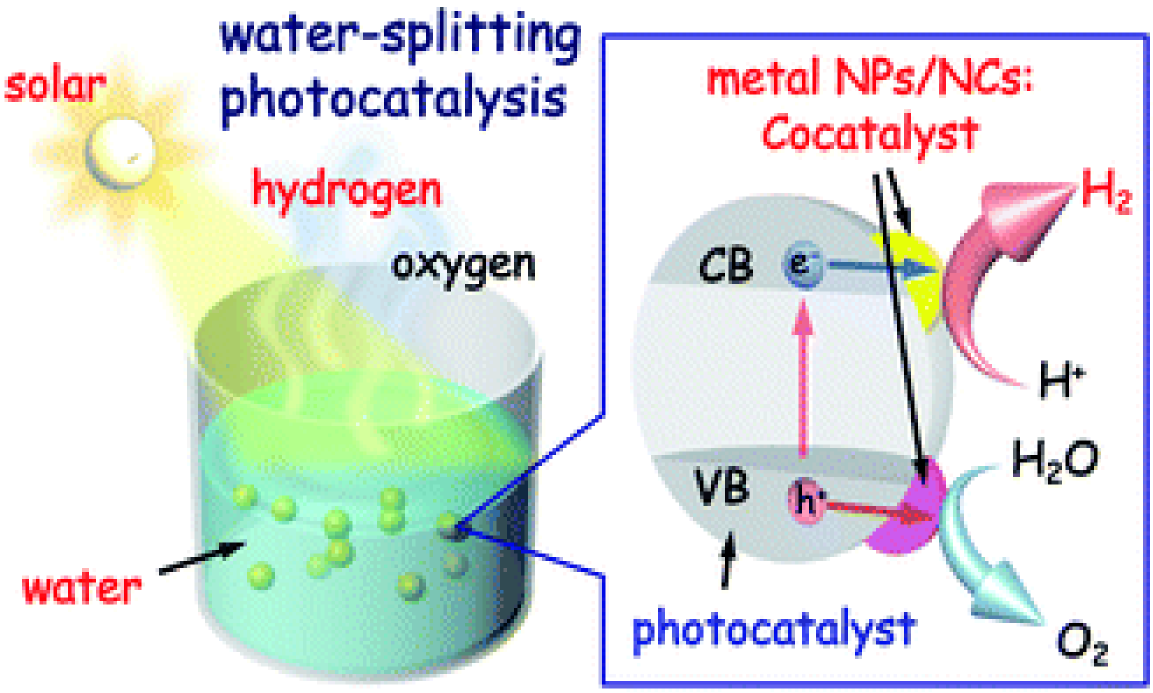

Fig 3: Solar Water Splitting Process

Colloidal Quantum Materials and Nanostructured Electrodes

Colloidal Quantum Materials

Nanotechnology bestows upon us the extraordinary ability to sculpt quantum dots and nanocrystals with meticulous precision. This mastery of size, shape, and composition opens the door to an array of tunable electronic properties. These nanoscale artisans are perfectly suited for the art of light absorption and charge separation. Through the finesse of nanoscale engineering, these materials transform into bespoke agents, primed to capture specific wavelengths of light and elegantly orchestrate the seamless transfer of charge carriers (Fig 4).

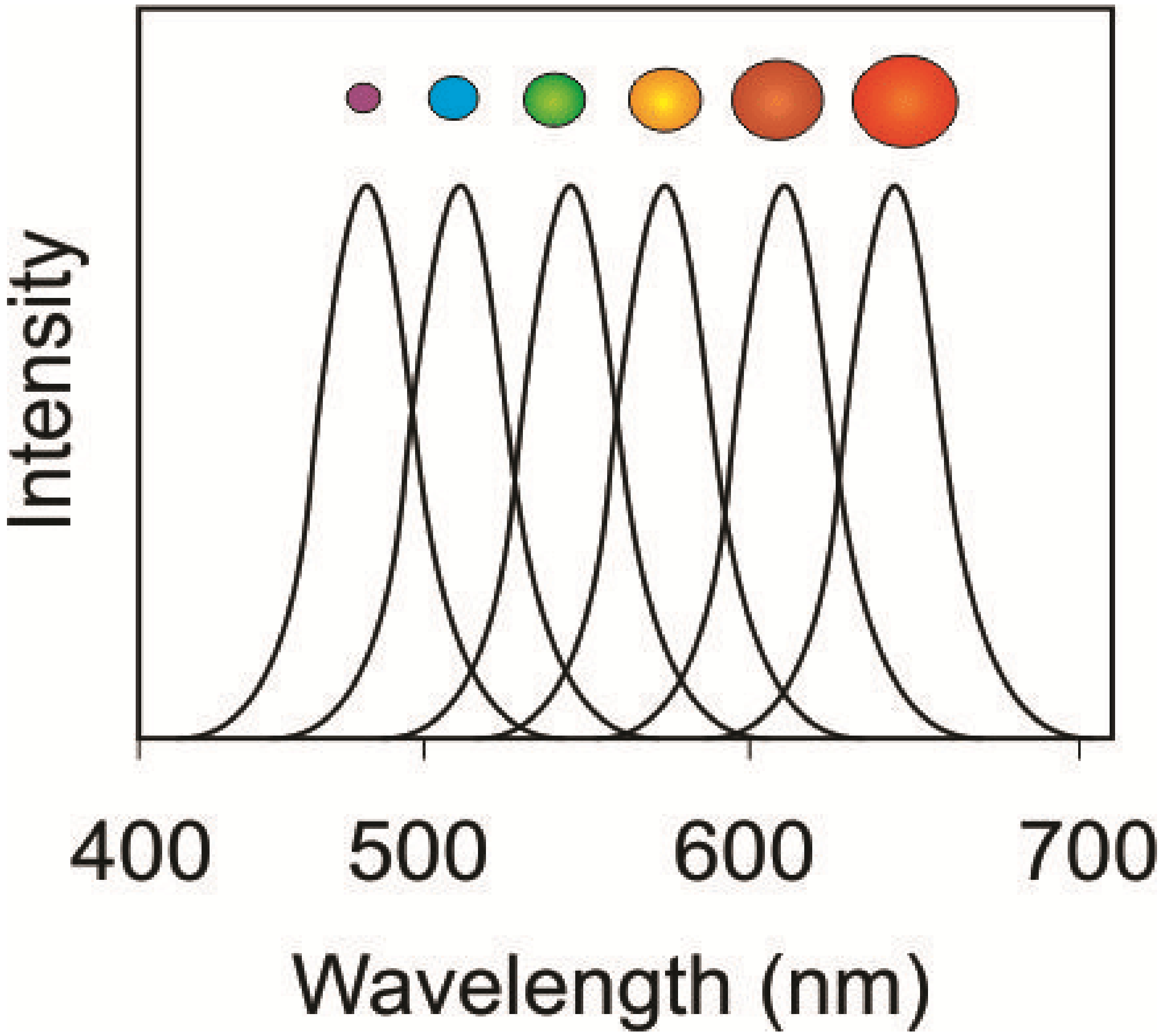

Fig 4: Quantum Dot characterization

Nanostructured Electrodes

In the realm of nanotechnology, custom-designed, high-surface-area electrodes take various forms, such as nanowires and porous structures. These intricate structures provide numerous active sites for efficient electrocatalysis, akin to a bustling city square. They promote electron and ion flow, resonating with conductivity. The synergy between colloidal quantum materials and nanostructured electrodes exemplifies the transformative potential of nanotechnology. This precision work at the nanoscale fuels hopes for sustainable solar-to-fuel conversion, painting a greener and cleaner energy landscape (Fig 5.).

The "Electrochemical Leaf

The "Electrochemical Leaf" concept is a vision of replicating nature's efficient photosynthesis by creating an artificial system to convert sunlight into chemical fuels, primarily hydrogen (Fig. 6). It relies on carefully engineered materials and components, holding great promise for a wide range of scientific and technological advancements [13]. Here's a recap of its far-reaching impact:

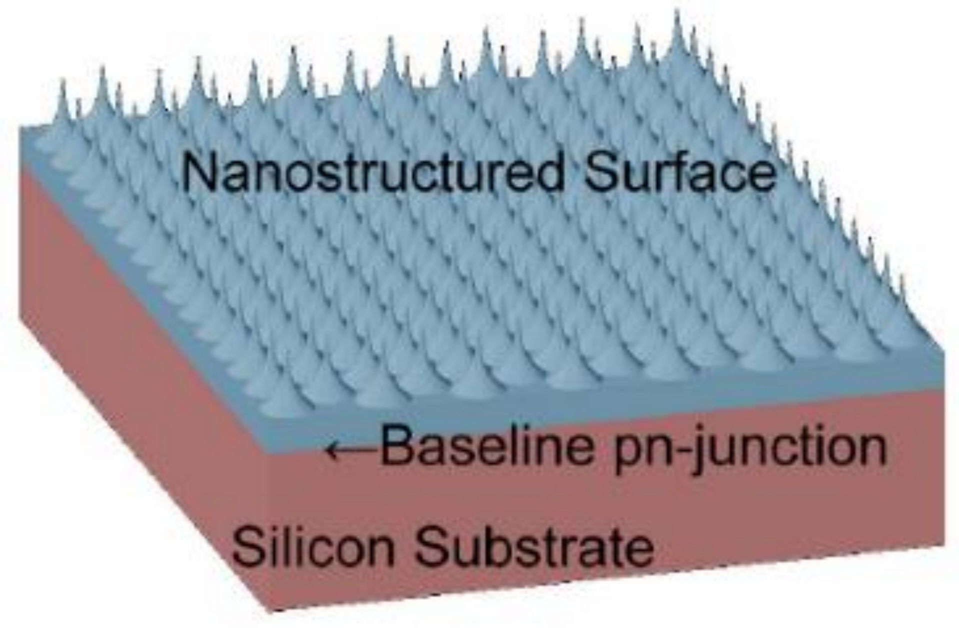

Fig 5: Nanostructured Electrodes

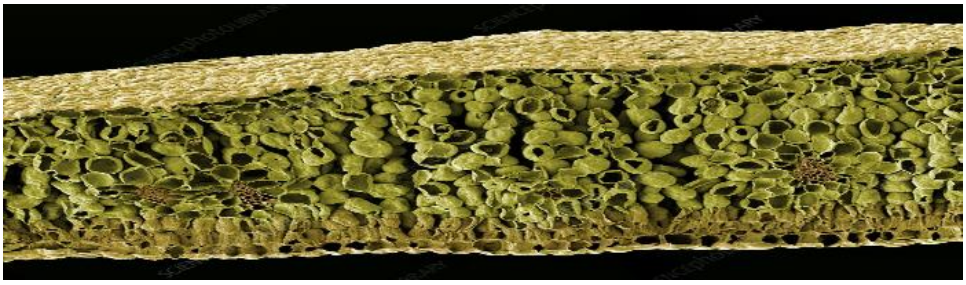

Fig 6: Electrochemical Leaf's Cell

Energy Production

The "Electrochemical Leaf" stands to revolutionize renewable energy production by efficiently converting sunlight into storable chemical fuels. This innovation offers a pivotal contribution to the development of a clean and sustainable energy future [14].

Energy Storage

Serving as a means of generating chemical fuels, the "Electrochemical Leaf" offers a promising avenue for large-scale, long-term energy storage. These produced fuels can be stockpiled and deployed during periods of low sunlight or heightened energy demand, alleviating a central challenge in renewable energy. Also chemical fuels synthesized by the "Electrochemical Leaf" serve as a clean, efficient energy source for diverse applications, spanning transportation and stationary power [15].

Environmental Impact

Through the direct conversion of solar energy into chemical fuels, the "Electrochemical Leaf" has the potential to curtail greenhouse gas emissions and diminish dependence on fossil fuels. It aligns harmoniously with global efforts to combat climate change and mitigate environmental impact.

Scientific Understanding and Technological Innovation

The "Electrochemical Leaf" concept shines a light on the intricacies of energy conversion and artificial photosynthesis and the vast realm of nanotechnology. This concept nurtures innovation in materials science, catalysis, and device design, pushing the boundaries of solar energy conversion and ushering in promising avenues for technological progress.

Conclusion:

In essence, this roadmap research illuminates a promising future where nanotechnology's precision at the nanoscale reignites hope for superior efficiency and sustainability in catalysis and solar energy conversion. Innovations spanning solar-to-fuel conversion, solar water splitting, and photovoltaics, among others, propel us toward a realm of sustainable energy solutions. Further advancements in nanomaterials, quantum dots, and nanostructured electrodes will lead to highly efficient and environmentally friendly energy conversion systems. Symbolizing this transformation is the "Electrochemical Leaf." Globally, nanotechnology remains a powerful driver, leading us into uncharted territories of energy production and storage. Through continuous advancements in nanomaterials and nanostructured electrodes, scientists are ready to create the path to highly efficient and eco-friendly energy conversion systems, painting a landscape of sustainable energy. This journey promises a cleaner environment, economic prosperity, and democratized access to renewable energy, ultimately illuminating a brighter future for all.

REFERENCES

1. [1] U Banin, N Waiskopf, L Hammarström, G Boschloo, M Freitag, E M J Johansson, J Sá, H Tian, M B Johnston, L M Herz, R L Milot, M G Kanatzidis, W Ke, I Spanopoulos, K L Kohlstedt, G C Schatz, N Lewis, T Meyer, A J Nozik, M C Beard, F Armstrong, C F Megarity, C A Schmuttenmaer, V S Batista and G W Brudvig. Nanotechnology for catalysis and solar energy conversion, 2021 *Nanotechnology*, 32 042003.
2. [2] Swick S M, Gebraad T, Jones L, Fu B, Aldrich T J, Kohlstedt K L, Schatz G C, Facchetti A and Marks T J, Building blocks for high-efficiency organic photovoltaics: interplay of molecular, crystal, and electronic properties in post-fullerene ITIC ensembles, *Chem Phys Chem*. 2019, 20, 2608-2626.
3. [3] McCrory C C L, Jung S, Ferrer I M, Chatman S M, Peters J C and Jaramillo T F, Benchmarking hydrogen evolving reaction and oxygen evolving reaction electrocatalysts for solar water splitting devices, *J.Am.Chem.Soc*. 2015, 137, 13, 4347–4357.
4. [4] Morello G, Armstrong F., The electrochemical leaf: driving and observing nanoconfined enzyme cascades, 2020, A Thesis submitted for the degree of Doctor of Philosophy, University of Oxford.
5. [5] Yossef. E. Panfil, Dr. Meirav Oded, Prof. Uri Banin., Colloidal Quantum Nanostructures: Emerging Materials for Display Applications 2017, *Angewandte Chemie International Edition*, Volume 57, Issue 16: 350 Years of Merck KGaA, Darmstadt, GermanyApr 2018, Pages 4105-4428.
6. [6] S.A. Olaleru, J.K. Kirui, D. Wamwangi, K.T. Roro, B. Mwakikunga, Perovskite solar cells: The new epoch in photovoltaics, *Solar Energy*, Volume 196, 15 January 2020, Pages 295-309.
7. [7] Zhihao Xu, Sang-Hyun Chin, Bo-In Park, Yuan Meng, Sunok Kim, Sangmoon Han, Yimeng Li, Dong-Hwan Kim, Beom-Soo Kim, Jin-Wook Lee, Sang-Hoon Bae, Advancing perovskite solar cell commercialization: Bridging materials,

vacuum deposition, and AI-assisted automation, *Next Materials*, Volume 3, April 2024, 100103.

8. [8] Mohammad Ismail Hossain, Md. Shahiduzzaman, Safayet Ahmed, Md. Rashedul Huqe, Wayesh Qarony, Ahmed Mortuza Saleque, Md. Akhtaruzzaman, Dietmar Knipp, Yuen Hong Tsang, Tetsuya Taima, Juan Antonio Zapien, Near field control for enhanced photovoltaic performance and photostability in perovskite solar cells, *Nano Energy*, Volume 89, Part A, November 2021, 106388.
9. [9] Sana Kainat, Junaid Anwer, Abdul Hamid, Nafisa Gull, Shahzad Maqsood Khan, Electrolytes in Lithium-Ion Batteries: Advancements in the Era of Twenties (2020's), *Materials Chemistry and Physics*, Volume 313, 1 February 2024, 128796.
10. [10] Fengshuo Hu, Chaoyu Dong, Luyu Tian, Yunfei Mu, Xiaodan Yu, Hongjie Jia, CWGAN-GP with residual network model for lithium-ion battery thermal image data expansion with quantitative metrics, *Energy and AI*, Volume 16, May 2024, 100321.
11. [11] Zhengfei Yang, Yueyue Zhong, Minghong Fan, Yongqi Yin, Huaiguo Xue, Weiming Fang, Metal-organic framework-derived leaf-like and stick-like Co3O4 for electrochemical sensing of H2O2, *Microchemical Journal*, Volume 197, February 2024, 109829.
12. [12] Mohammad Aadil, Muhammad Ali Khan, Safira Ananda Repycha, Mosab Kaseem, Utilizing a defective MgO layer for engineering multifunctional Co-MOF hybrid materials with tailored leaf-like and polyhedral structures for optimal electrochemical and photocatalytic activities, *Nano Materials Science*, Available online 15 December 2023.
13. [13] Huixia He, Wenyu Wei, Yongling An, Jinkui Feng, Jianxi Xiao, Leaf-like copper oxide mesocrystals by collagen-assisted biomineralization show attractive biofunctional and electrochemical properties, **Materials Advances**, Volume 3, Issue 1, 4 January 2022, Pages 245-253.
14. [14] Keqiang Ding, Jiasheng Chen, Dongyue Zhang, Fujuan Shi, Boxia Li, Wenyue Tian, Xiangming He, Li Wang, Hui Wang, Electrochemical deposition of leaf stalk-shaped polyaniline doped with sodium dodecyl sulfate on aluminum and its use as a novel type of current collector in lithium ion batteries, *Synthetic Metals*, Volume 278, August 2021, 116837.
15. [15] Ramesh Y. Adhikari, Nicole E. Harmon, K. Paige Williams, Pristine leaf based electrochemical resistive switching device, *Applied Materials Today*, Volume 24, September 2021, 101077.

