

Research Article

Artificial Leaves: Bio-Inspired Systems for Sustainable Energy and Environmental Solutions

Priyank Kumar Shivam* , Kurumbeparambil Mohanan Priyan ,
Bheem Pad Mahato 

Faculty of Education, ICFAI University Tripura, Agartala, India

Abstract

Leaves are the site of photosynthesis. Photosynthesis is the remarkable natural process by which plants, algae, and certain bacteria convert sunlight, water, and carbon dioxide into oxygen and energy-rich organic compounds. This complex process is broadly divided into two main stages: the Light-dependent Reaction and the Light-independent Reaction (or Dark Reaction). The Light-dependent Reaction captures light energy to produce ATP and NADPH. These products then power the Light-independent Reaction (Calvin Cycle), which fixes carbon dioxide to create sugars. The entire process requires intricate coupling (e.g., in chloroplasts) to ensure the efficiency and regulation of these stages. Artificial leaves are bio-inspired devices that mimic natural photosynthesis to convert solar energy into chemical fuels and sequester CO₂. These systems integrate light-absorbing materials, catalysts, and biomimetic designs to enable efficient water splitting, hydrogen production, and CO₂ reduction. This review examines principles, recent advancements, and challenges in artificial leaf technology, focusing on system engineering, material innovations, and applications. Notable progress includes solar-to-hydrogen efficiencies above 10% and selective CO₂ reduction using triazine-based membranes. Modern designs prioritize lightweight, flexible, and floating configurations for scalability, allowing deployment on water without land competition. Systems have scaled to 100 cm² with 24-hour stability, but durability, efficiency, and manufacturing challenges persist. Future priorities include improving fluid dynamics, mass transport, and catalysts, while exploring multifunctional uses like water purification. Artificial leaves hold transformative potential for sustainable, decentralized energy production and carbon sequestration, particularly in infrastructure-limited regions, by converting CO₂ into valuable products.

Keywords

Artificial Photosynthesis, Solar Fuels, Water Splitting, CO₂ Reduction, Biomimetic Design, Sustainable Energy

1. Introduction

1.1. Photosynthesis: Nature's Energy Solution

Photosynthesis is the remarkable natural process by which plants, algae, and certain bacteria convert sunlight, water, and carbon dioxide into oxygen and energy-rich organic com-

pounds. This fundamental biological process is responsible for producing the oxygen we breathe and forms the foundation of nearly all food chains on Earth. The word "photosynthesis" comes from the Greek words "photo" (light) and "synthesis" (putting together), literally meaning "creating

*Corresponding author: priyankkumarshivam@gmail.com (Priyank Kumar Shivam)

Received: 8 September 2025; **Accepted:** 28 September 2025; **Published:** 18 October 2025



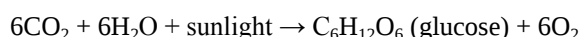
Copyright: © The Author(s), 2025. Published by Science Publishing Group. This is an **Open Access** article, distributed under the terms of the Creative Commons Attribution 4.0 License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution and reproduction in any medium, provided the original work is properly cited.

with light."

At its core, photosynthesis serves several critical functions in our biosphere:

- 1) It converts solar energy into chemical energy stored in glucose and other organic molecules
- 2) It produces oxygen as a byproduct, essential for aerobic life forms
- 3) It removes carbon dioxide from the atmosphere, playing a vital role in the global carbon cycle
- 4) It forms the basis of most food webs, providing energy for nearly all living organisms

The overall process can be summarized in the simple chemical equation:



1.2. The Light Reaction: Capturing Solar Energy

The first stage of photosynthesis, the light reaction (also called the light-dependent reaction), takes place in the thylakoid membranes of chloroplasts. During this phase:

- 1) Chlorophyll and other pigments in photosystems I and II absorb photons from sunlight
- 2) This energy excites electrons, which are passed along an electron transport chain
- 3) Water molecules are split (photolysis), releasing oxygen as a byproduct
- 4) The energy from excited electrons is used to pump protons across the thylakoid membrane, creating a concentration gradient
- 5) This gradient drives ATP synthase to produce ATP (adenosine triphosphate)
- 6) NADP^+ is reduced to NADPH by accepting energized electrons

The primary outputs of the light reaction are ATP (energy currency), NADPH (reducing power), and oxygen. These products are essential for the next stage of photosynthesis.

1.3. The Dark Reaction: Carbon Fixation

The second stage, known as the dark reaction or light-independent reaction (also called the Calvin cycle), occurs in the stroma of chloroplasts. Despite its name, this process doesn't necessarily occur in darkness but simply doesn't directly require light. During this phase:

- 1) Carbon dioxide from the atmosphere enters the leaf through small pores called stomata
- 2) The enzyme RuBisCO (the most abundant protein on Earth) captures CO_2 molecules
- 3) Using the ATP and NADPH produced during the light reaction, the plant converts CO_2 into simple sugars through a series of chemical reactions
- 4) These sugars can be used immediately for energy, converted to starch for storage, or transformed into other

organic molecules like cellulose for structural support

This carbon fixation process is how plants convert atmospheric carbon dioxide into the building blocks for all plant structures and stored energy.

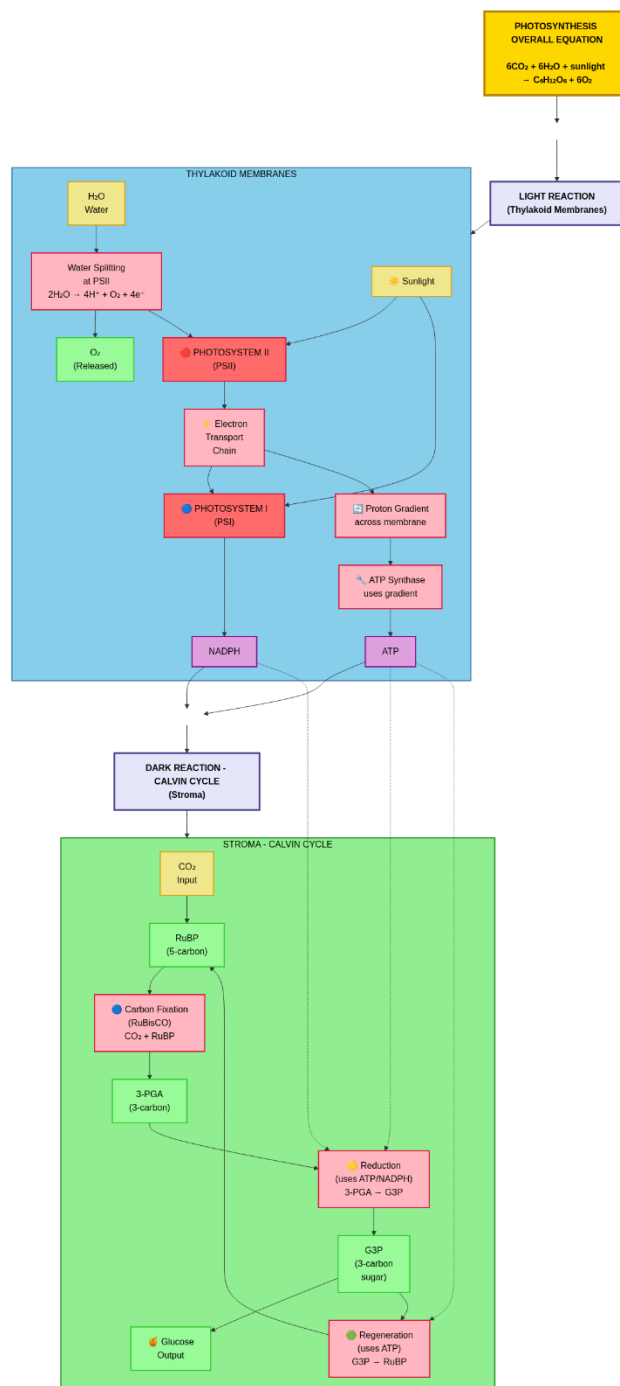


Figure 1. Photosynthesis.

1.4. C-C Coupling in Photosynthesis

C-C coupling in photosynthesis refers to the initial carbon fixation step where carbon dioxide (CO_2) is chemically bonded to a carbon-containing molecule, typically ribu-

lose-1,5-bisphosphate (RuBP), to form a new carbon-carbon bond. This process is catalyzed by the enzyme RuBisCO (Ribulose-1,5-bisphosphate carboxylase/oxygenase) and results in the formation of two molecules of 3-phosphoglycerate (3-PGA), a three-carbon compound. It is a critical reaction in the carbon assimilation pathway, enabling the conversion of inorganic CO₂ into organic molecules that can be used for energy and growth. The term "C-C coupling" specifically highlights the creation of this new carbon-carbon bond during CO₂ fixation.

This process occurs in the stroma of chloroplasts in photosynthetic organisms, where RuBisCO is located. It takes place during the Calvin-Benson cycle, specifically in the first stage known as the carbon fixation phase. This stage is part of the light-independent reactions (or dark reactions) of photosynthesis, which follow the light-dependent reactions that generate ATP and NADPH. C-C coupling is essential for incorporating atmospheric CO₂ into the biochemical pathways that produce sugars and other carbohydrates, primarily in plants, algae, and cyanobacteria.

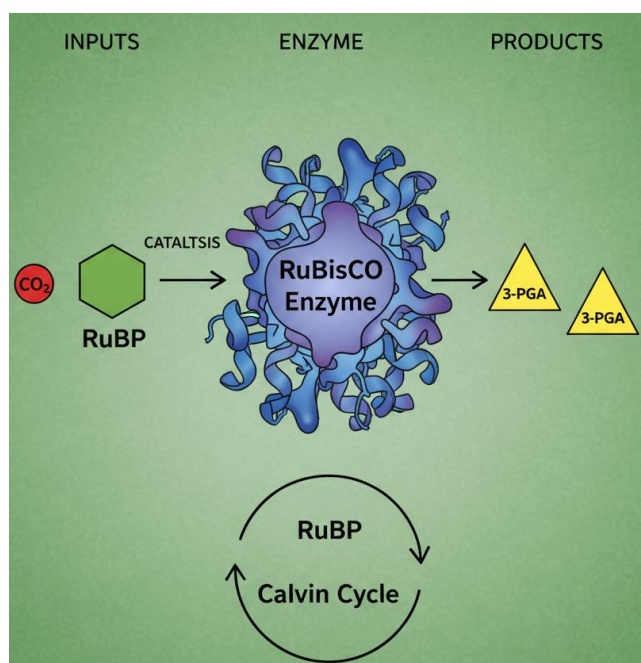


Figure 2. C-C Coupling in Photosynthesis.

1.5. Artificial Leaves: Inspired by Nature's Genius

Natural photosynthesis is a highly efficient process that has evolved over billions of years. It converts solar energy into chemical energy, producing oxygen and energy-rich molecules through water splitting and CO₂ fixation. Artificial leaves aim to replicate these processes using earth-abundant materials and advanced engineering to generate clean fuels

(e.g., hydrogen, methane, formate) and mitigate atmospheric CO₂.

The core mechanisms of artificial leaves involve light absorption, charge separation, and catalytic reactions, often designed to operate under benign conditions such as neutral water and standard solar illumination (1 sun, 100 mW/cm²) [1]. Unlike traditional solar panels that convert sunlight to electricity, artificial leaves convert sunlight directly into chemical fuels, offering advantages for energy storage and transport.

This paper synthesizes insights from recent research, particularly from studies by Nocera (2012), Gao et al. (2023), and Bensaid et al. (2012), to provide a comprehensive overview of artificial leaf technology, its applications, and future directions [1, 2, 5]. By understanding and improving upon nature's photosynthetic mechanisms, researchers are developing sustainable solutions for global energy challenges while simultaneously addressing climate change through carbon capture and utilization.

2. Key Studies on Artificial Leaf Systems – Materials, Metrics, and Innovations

The table presents a concise review of three pioneering bio-inspired artificial leaf systems for sustainable energy and environmental solutions, drawing from recent studies to highlight advancements in mimicking natural photosynthesis for CO₂ reduction and water splitting. Nocera et al. (2012) introduced an early artificial leaf utilizing cobalt-phosphate (Co-OEC) as the primary material, achieving self-healing metrics in neutral water environments with earth-abundant elements, and demonstrating lab-scale, self-healing capabilities. Building on this, Gao et al. (2023) advanced the technology through copper oxide (CuO)-based triazine frameworks, enabling 1240 μmol g⁻¹ CO yield with over 90% selectivity in metal-free gas-solid CO₂ reduction, supporting four hours of continuous operation and 100 cm² device deployment for high solar-to-fuel efficiency in decentralized water-deprived settings. Most recently, Huang et al. (2024) developed a rootless duckweed-inspired Janus plasmonic nanosheet system, leveraging copper phthalocyanine (CuPc) for efficient CO₂ sequestration at adjustable rates, incorporating biomimetic plasmonic enhancement mechanisms and demonstrating floating prototype integration for ecosystem-scale environmental remediation. Collectively, these entries underscore the evolution from foundational lab prototypes to scalable, efficient, and deployable systems, emphasizing earth-abundant materials, high selectivity, and bio-mimetic designs to address global challenges in carbon capture and renewable fuel production.

Table 1. Key Studies on Artificial Leaf Systems – Materials, Metrics, and Innovations.

Study	Primary Focus	Key Materials	Performance Metrics	Unique Innovation	Scale/Stability
Nocera (2012)	Water splitting & H ₂ production	Co-OEC catalyst, NiMoZn alloy, amorphous Si	Stable operation in neutral water	Self-healing earth-abundant catalysts	Laboratory scale, self-healing
Gao et al. (2023)	CO ₂ reduction using COF	Triazine-based COF membrane	1240 $\mu\text{mol g}^{-1}\text{CO}$ yield, ~100% selectivity	Metal-free gas-solid CO ₂ reduction	4 hours continuous operation
Andrei et al. (2022)	Floating perovskite devices	Perovskite-BiVO ₄ , flexible substrates	High solar-to-fuel efficiency, flotation	Water-deployable floating devices	100 cm ² devices, outdoor deployment
Huang et al. (2024)	Rootless duckweed-inspired	Janus plasmonic nanosheets	Efficient floating solar-chemical conversion	Biomimetic plasmonic enhancement	Floating prototype demonstration
Zhu et al. (2024)	Enzymatic CO ₂ sequestration	Cellulose, carbonic anhydrase enzyme	Adjustable CO ₂ sequestration rate	Stomatal regulation mechanism	Ecosystem integration capability

3. Core Mechanisms of Artificial Leaves

3.1. Mimicking Natural Photosynthesis

Natural leaves absorb sunlight to generate electron-hole pairs, which are spatially separated to drive water oxidation at the oxygen-evolving complex (OEC) of photosystem II (PSII) and proton/electron reduction at photosystem I (PSI). The OEC oxidizes water to produce oxygen, while electrons and protons are used to form NADPH via ferredoxin-NADP⁺ reductase [1]. Artificial leaves replicate this process by integrating:

- 1) **Light-absorbing materials:** Photovoltaics (e.g., amorphous silicon, perovskite) or semiconductors (e.g., N-doped TiO₂) capture solar photons to generate a wireless current.
- 2) **Catalysts:** Oxygen-evolving catalysts (e.g., cobalt-phosphate cluster, Co-OEC) and hydrogen-evolving catalysts (e.g., NiMoZn alloy) facilitate water splitting.
- 3) **Charge separation systems:** Hierarchical or biomimetic structures enhance electron-hole separation and transport [1, 6].

It's important to note that the Co-OEC (cobalt-phosphate or Co-Pi catalyst) mimics the *function* rather than the exact structure of the PSII-OEC. While the natural OEC contains a Mn₃CaO₄ cubane structure, the Co-OEC is a cobalt-phosphate cluster that functionally mimics the natural system by self-assembling from earth-abundant cobalt ions and operating in neutral water with self-healing properties [1]. This functional mimicry enables robust, low-cost systems for solar-to-fuel conversion without replicating the exact molecular structure of natural photosynthesis.

3.2. System Design Principles

Effective artificial leaves require integrated system design, combining catalysts, electrodes, membranes, and sensitizers while optimizing mass/charge transport, fluid dynamics, and device robustness. Bensaid et al. emphasize that system-level engineering must be considered from the outset to ensure scalability and efficiency [5]. Key design principles include:

- 1) **Earth-abundant materials:** Using non-precious metals (e.g., Co, Ni, Mo) reduces costs and enhances accessibility.
- 2) **Biomimetic structures:** Leaf-like or stomatal-inspired designs improve light harvesting and gas exchange.
- 3) **Scalability:** Lightweight, flexible, and floating devices enable deployment in diverse environments, such as open water [9].

4. Key Applications of Artificial Leaves

4.1. Water Splitting and Hydrogen Production

Artificial leaves for water splitting generate hydrogen as a clean fuel. A notable example is Nocera's triple-junction amorphous silicon photovoltaic interfaced with a Co-OEC for oxygen evolution and a NiMoZn alloy for hydrogen production [1]. This system operates in neutral water, is self-healing, and uses a conductive metal oxide coating to stabilize silicon, eliminating the need for platinum. Hierarchical structures, inspired by natural leaves, further enhance light harvesting and charge separation, achieving efficient photochemical hydrogen production [6]. The use of earth-abundant materials and low-cost manufacturing makes these systems viable for distributed solar-to-fuel applications in resource-constrained

regions [1].

Recent advancements have pushed solar-to-hydrogen efficiencies to exceed 10% in some systems, representing significant progress towards commercial viability. These high-efficiency systems typically employ perovskite-based photoelectrodes with optimized electron transport layers and carefully engineered encapsulation to enhance durability [2, 7].

4.2. CO₂ Reduction and Carbon Sequestration

Artificial leaves also enable photoreduction of CO₂ into value-added chemicals, addressing climate change by converting greenhouse gases into fuels. Gao et al. developed a triazine-based covalent organic framework (COF) membrane, inspired by leaf microstructures, achieving a record CO yield of 1240 $\mu\text{mol g}^{-1}$ in 4 hours with $\sim 100\%$ selectivity under metal-free, photosensitizer-free, gas-solid conditions [2]. This remarkable performance was achieved specifically under gas-solid interface conditions, which is an important experimental detail that distinguishes their approach from liquid-phase systems. The COF's steady light-harvesting sites, efficient catalytic centres, and fast charge/mass transfer configuration highlight the synergy of chemical and physical design. Other systems, such as Z-scheme biocatalytic devices and 3D-printed prototypes, selectively produce CO, methane, and formate [3]. Cellulosic artificial leaves like Eco Leaf mimic stomatal function, offering adjustable enzymatic CO₂ sequestration for ecological integration [4].

4.3. Multifunctional Applications

Beyond energy, artificial leaves have applications in water collection and microfluidics. Biomimetic vein structures enable directional droplet manipulation and efficient water transport, inspired by natural leaf venation [7]. Additionally, MnO₂-based artificial leaves with atomic-scale biomimicry enhance stability for battery anodes, demonstrating versatility in energy storage [8].

5. Recent Innovations

5.1. Structural and Material Advances

Recent designs prioritize lightweight, flexible, and floating artificial leaves to enhance scalability. Andrei et al. developed perovskite-BiVO₄ devices on flexible substrates, achieving high solar-to-fuel efficiencies and enabling outdoor deployment on water without land use competition [9]. These devices achieve flotation through gas bubble formation during operation, with bubbles formed under illumination enabling 30-100 mg cm^{-2} devices to float on water surfaces. This elegant self-buoyancy mechanism eliminates the need for additional flotation components, simplifying design and reducing weight.

Huang et al.'s rootless duckweed-inspired leaves use Janus plasmonic nanosheets for efficient, floating solar-to-chemical conversion [10]. These innovations leverage biomimetic principles to optimize light absorption, charge transport, and environmental adaptability.

5.2. System-Level Engineering

Bensaid et al. highlight the importance of system-level engineering to address constraints in mass/charge transport, fluid dynamics, and sealing [5]. For instance, integrating catalysts with electrodes and membranes requires careful consideration of fluid flow and ion transport to maintain efficiency. Floating designs further complicate engineering, necessitating robust sealing and stability in dynamic aquatic environments [9].

5.3. Advanced Catalysts and Electrodes

Recent catalyst advancements include self-assembling Co-OEC, which undergoes proton-coupled electron transfer akin to the Kok cycle of PSII, and NiMoZn alloys that replace platinum for hydrogen evolution [1]. Advanced electrodes, such as those with conductive metal oxide coatings, stabilize light-absorbing materials in aqueous environments [1, 5].

6. Challenges and Future Directions

6.1. Engineering Challenges

Despite progress, artificial leaves face challenges in:

- 1) **Scalability:** Recent advances have demonstrated scaling up to 100 cm^2 artificial leaves with comparable performance to smaller (1.7 cm^2) counterparts. However, manufacturing processes for mass production still require further development to achieve cost-effective deployment at industrial scales.
- 2) **Stability:** Current large-scale systems typically maintain stability for around 24 hours of continuous operation—significant progress but still short of commercial viability targets requiring thousands of hours. Long-term operation in harsh environments (e.g., open water) demands more durable materials and enhanced self-healing mechanisms.
- 3) **Efficiency:** While some recent designs have achieved solar-to-hydrogen efficiencies exceeding 10%, surpassing natural photosynthesis, further optimization of charge separation and catalytic performance is needed to reach the 15-20% efficiency threshold considered economically competitive for hydrogen production [5].

6.2. Research Priorities

The advancement of artificial leaf technology requires focused research efforts across multiple disciplines. While sig-

nificant progress has been made, several critical research priorities remain to be addressed for achieving commercial viability and widespread implementation:

6.2.1. System-Level Optimization

Current artificial leaf research often focuses on individual components (catalysts, light absorbers, etc.) rather than integrated systems. Future priorities should include:

- 1) **Integrated Design Approaches:** Developing computational models that simultaneously optimize fluid dynamics, mass transport, light harvesting, and chemical kinetics within a single framework. This holistic approach would enable researchers to identify and address system-level bottlenecks that limit overall performance.
- 2) **Membrane Engineering:** Creating advanced ion-selective membranes that facilitate efficient proton transport while preventing product crossover, particularly crucial for systems generating multiple products (e.g., H_2 and O_2). Innovations in membrane materials could potentially leverage biomimetic principles, such as the selective ion channels found in cell membranes.
- 3) **Thermal Management:** Designing systems that effectively manage heat generation during operation, as excessive temperatures can reduce efficiency and accelerate degradation. Passive cooling mechanisms inspired by natural leaf structures could offer lightweight, low-cost solutions.
- 4) **Robust Encapsulation:** Developing weatherproof sealants and encapsulation methods that protect sensitive components while allowing efficient gas exchange, enabling long-term outdoor deployment in diverse environments including open water bodies [5, 9].

6.2.2. Material Innovation

Continued advancement in materials science is essential for enhancing performance and reducing costs:

- 1) **Earth-Abundant Catalysts:** Further development of non-precious metal catalysts with activity approaching that of platinum-group metals. Research should focus on understanding structure-activity relationships to rationally design catalysts with optimized active sites, particularly for oxygen evolution and CO_2 reduction reactions.
- 2) **Self-Healing Materials:** Expanding self-healing capabilities beyond the Co-OEC to include semiconductor interfaces and protective coatings, potentially incorporating microcapsule-based or intrinsically self-healing polymers that activate upon degradation.
- 3) **Stable Light Absorbers:** Developing photovoltaic or semiconductor materials that maintain stability in aqueous environments for thousands of hours while achieving high quantum efficiencies across the solar spectrum. Hybrid organic-inorganic materials and tandem architectures offer promising paths forward.
- 4) **Nanoscale Architecture:** Engineering hierarchical nanostructures that maximize surface area, light ab-

sorption, and mass transport while maintaining mechanical stability, potentially drawing inspiration from the intricate internal structure of natural leaves [6, 10].

6.2.3. Multifunctional Applications

Expanding artificial leaf functionality beyond energy production could significantly enhance their value proposition:

- 1) **Integrated Water Purification:** Developing systems that simultaneously generate fuel and purify water, leveraging the reactive oxygen species produced during water oxidation to degrade organic contaminants or inactivate pathogens. This dual functionality would be particularly valuable in regions with limited access to clean water.
- 2) **Nutrient Recovery:** Engineering artificial leaves capable of extracting and concentrating valuable nutrients (phosphorus, nitrogen, potassium) from wastewater or agricultural runoff, contributing to circular economy approaches while reducing environmental pollution.
- 3) **Smart Responsive Systems:** Creating adaptive artificial leaves that respond to environmental conditions (light intensity, temperature, humidity) by adjusting their operation mode, maximizing efficiency across varying conditions similar to how natural leaves regulate stomatal opening.
- 4) **Energy Storage Integration:** Developing direct interfaces between artificial leaves and advanced energy storage systems, such as flow batteries or electrochemical capacitors, enabling efficient capture and utilization of intermittent solar energy [7, 8].

6.2.4. Scale-Up and Manufacturing

Transitioning from laboratory prototypes to commercial products requires significant advances in manufacturing:

- 1) **Roll-to-Roll Processing:** Developing continuous manufacturing methods for flexible artificial leaves, enabling high-throughput, low-cost production similar to printed electronics. This approach could dramatically reduce capital costs compared to traditional semiconductor manufacturing.
- 2) **Modular Designs:** Creating standardized, interconnectable modules that can be deployed at various scales, from residential applications to industrial installations, with minimal customization requirements.
- 3) **In-Situ Monitoring:** Integrating sensors and diagnostic capabilities within artificial leaf systems to enable real-time performance monitoring, fault detection, and predictive maintenance, enhancing longevity and reliability.
- 4) **Life Cycle Assessment:** Conducting comprehensive analyses of environmental impacts throughout the product life cycle, from raw material extraction to end-of-life disposal or recycling, ensuring that artificial leaves deliver net positive environmental benefits.

6.2.5. Environmental Integration and Biocompatibility

For large-scale deployment, particularly in natural environments:

- 1) Ecological Impact Studies: Investigating the effects of artificial leaf deployment on aquatic ecosystems, including potential impacts on dissolved oxygen levels, pH, and microbial communities. Long-term field studies are essential to identify and mitigate any unintended consequences.
- 2) Biomimetic Gas Exchange: Developing advanced gas management systems inspired by plant stomata, as demonstrated by Eco Leaf's adjustable CO₂ sequestration capability [4]. Such systems could optimize CO₂ uptake while minimizing water loss, a critical consideration for deployment in water-scarce regions.
- 3) Biohybrid Systems: Exploring synergistic combinations of artificial components with living biological systems, such as algae or cyanobacteria, to create hybrid devices that leverage the strengths of both engineered and biological photosynthesis.
- 4) Circular Design Principles: Incorporating end-of-life considerations from the beginning, ensuring that materials can be easily separated for recycling or safe biodegradation, minimizing waste and environmental impact.

By addressing these research priorities through coordinated, interdisciplinary efforts, artificial leaf technology can advance from promising laboratory demonstrations to transformative solutions for global energy and environmental challenges. The convergence of breakthroughs across these domains would enable artificial leaves to achieve the efficiency, durability, and scalability required for commercial success while maximizing their potential for positive societal impact.

6.3. Societal Impact

Artificial leaves offer a pathway to decentralized, sustainable energy systems, particularly for non-legacy regions with limited infrastructure. By providing low-cost, distributed solar-to-fuel solutions, they can democratize access to clean energy and mitigate climate change through CO₂ reduction and sequestration [1, 2]. The unique ability of these systems to operate without complex supporting infrastructure makes them especially valuable for remote communities and developing regions where conventional energy distribution networks are impractical or prohibitively expensive. Unlike traditional solar photovoltaics that require grid connections or expensive battery storage, artificial leaves produce storable chemical fuels that can be used on demand for cooking, heating, electricity generation, and transportation. Nocera's vision of an "artificial leaf in every home" could transform energy access in rural areas of Africa, Asia, and Latin America, where an estimated 770 million people still lack reliable electricity [1]. The potential for these systems to operate with untreated water sources further enhances their

applicability in resource-constrained environments, enabling communities to simultaneously address energy needs and water purification challenges.

The economic implications of widespread artificial leaf deployment extend beyond energy accessibility to include job creation, resource independence, and new value chains. Manufacturing, installation, and maintenance of these systems could generate significant employment opportunities, particularly in regions currently dependent on imported fossil fuels. The distributed nature of artificial leaf technology could help flatten traditional energy hierarchies, reducing the market power of centralized energy providers and the geopolitical leverage of fossil fuel-rich nations. Furthermore, the ability of advanced artificial leaves to convert CO₂ into valuable chemical feedstocks creates economic incentives for carbon capture, potentially transforming carbon management from a regulatory burden into a profitable enterprise [2, 3]. This paradigm shift could accelerate the transition to circular carbon economies where atmospheric CO₂ becomes a renewable resource rather than a pollutant. Early economic analyses suggest that with continued improvements in efficiency and durability, artificial leaf systems could achieve hydrogen production costs competitive with fossil fuel-derived hydrogen within the next decade, particularly in regions with abundant solar resources.

The environmental and social benefits of artificial leaf technology extend far beyond climate change mitigation. By enabling energy production without land-use competition, floating artificial leaves could help preserve agricultural land and natural habitats while providing clean energy [9]. This stands in stark contrast to conventional biofuel approaches that often create tensions between food and fuel production. Additionally, the potential integration of water purification capabilities could address multiple sustainable development goals simultaneously, improving health outcomes and reducing time spent collecting water, particularly for women and girls in developing regions. The visually unobtrusive nature of these systems, especially when deployed on water surfaces, minimizes aesthetic impacts compared to conventional renewable energy installations, potentially reducing community resistance to adoption. Perhaps most importantly, artificial leaves embody a fundamentally different relationship between humanity and natural resources, one that mimics natural processes rather than extracting finite reserves, potentially helping shift cultural perspectives toward more sustainable models of production and consumption. As artificial leaf technology matures from laboratory curiosity to commercial reality, its greatest impact may be in demonstrating that human ingenuity can create systems that work in harmony with natural cycles rather than in opposition to them.

7. Conclusion

Artificial leaves showcase a fusion of bioinspiration and advanced engineering, offering transformative potential for

energy and environmental solutions. Progressing from initial prototypes to systems with over 10% solar-to-hydrogen efficiency using earth-abundant materials, these innovations mimic photosynthesis for water splitting and CO₂ reduction under mild conditions. Recent floating designs enhance scalability by utilizing water surfaces, avoiding land-use conflicts and supporting industrial applications without ecological disruption. However, challenges in durability, efficiency, and cost-effective production persist, necessitating interdisciplinary research into self-healing materials, fluid dynamics, and robust encapsulation for varied environments. Successful development could democratize access to clean energy and water purification, especially in non-legacy regions, while fostering economic growth through carbon valorisation. Representing a shift from extraction to regeneration and centralization to distribution, artificial leaves could harmonize technology with nature, redefining carbon cycle interactions. With continued innovation, they may become a key pillar of a sustainable future, promoting planetary health.

Abbreviations

CO ₂	Carbon Dioxide
OEC	Oxygen-evolving Complex
PSII	Photosystem II
PSI	Photosystem I
COF	Covalent Organic Framework

Author Contributions

Priyank Kumar Shivam: Conceptualization, Formal Analysis, Methodology, Writing – original draft, Writing – review & editing

Kurumbeparambil Mohanan Priyan: Supervision, Validation, Writing – review & editing

Bheem Pad Mahato: Conceptualization, Data curation, Formal Analysis

Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] Nocera, D., 2012. The artificial leaf. *Accounts of Chemical Research*, 45(5), pp. 767-776. <https://doi.org/10.1021/ar2003013>
- [2] Gao, S., et al., 2023. Ingenious artificial leaf based on covalent organic framework membranes for boosting CO₂ photoreduction. *Journal of the American Chemical Society*. <https://doi.org/10.1021/jacs.2c11146>
- [3] Kumar, A., et al., 2021. Artificial leaf for light-driven CO₂ reduction: Basic concepts, advanced structures and selective solar-to-chemical products. *Chemical Engineering Journal*. <https://doi.org/10.1016/j.cej.2021.133031>
- [4] Zhu, X., et al., 2024. Artificial cellulosic leaf with adjustable enzymatic CO₂ sequestration capability. *Nature Communications*, 15. <https://doi.org/10.1038/s41467-024-49320-y>
- [5] Bensaid, S., et al., 2012. Towards artificial leaves for solar hydrogen and fuels from carbon dioxide. *ChemSusChem*, 5(3), pp. 500-521. <https://doi.org/10.1002/cssc.201100661>
- [6] Zhou, H., et al., 2010. Artificial inorganic leaves for efficient photochemical hydrogen production inspired by natural photosynthesis. *Advanced Materials*, 22. <https://doi.org/10.1002/adma.200902039>
- [7] Liang, X., et al., 2021. Artificial leaf for switchable droplet manipulation. *Langmuir*. <https://doi.org/10.1021/acs.langmuir.1c00799>
- [8] Jia, B., et al., 2019. Construction of MnO₂ artificial leaf with atomic thickness as highly stable battery anodes. *Advanced Materials*, 32. <https://doi.org/10.1002/adma.201906582>
- [9] Andrei, V., et al., 2022. Floating perovskite-BiVO₄ devices for scalable solar fuel production. *Nature*, 608, pp. 518-522. <https://doi.org/10.1038/s41586-022-04978-6>
- [10] Huang, Y., et al., 2024. A rootless duckweed-inspired flexible artificial leaf from plasmonic photocatalysts. *ACS Nano*. <https://doi.org/10.1021/acsnano.4c11435>