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Solar Leaves: How Plants Teach Us to Harvest Energy



BIOS4YOU
AR 2.0

BIO-INSPIRED STEM TOPICS FOR ENGAGING YOUNG GENERATIONS
THANKS TO THE USE OF AUGMENTED REALITY

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General topic of the learning path	Bio-Inspired Solar Technology: Learning from Nature to Harvest Energy
Specific name of the learning unit	Solar Leaves: How Plants Teach Us to Harvest Energy
Target user age	14-18 years
Learner prerequisites	Basic knowledge of Biology, Chemistry, Physics, and introductory Environmental Science
Description of the learning unit	This unit introduces students and teachers to bio-inspired solar technology, emphasizing how plants efficiently capture solar energy through photosynthesis and how scientists replicate these mechanisms for sustainable energy solutions. Using Augmented Reality (AR) tools, students will visualize the photosynthesis process, explore biohybrid solar cells, and experiment with nature-based solar panel designs. The unit fosters multidisciplinary learning by integrating biology, physics, chemistry, and engineering concepts with hands-on digital experiments.
Subject involved	Biology, Physics, Chemistry, Environmental Science, Engineering, Mathematics
Keywords	Photosynthesis, Solar Energy, Bio-Inspired, Biomimicry, Sustainability, Renewable Energy, AR, Interactive Learning, Smart Solar Technology
Key-skills, abilities, knowledge that can be acquired	- Understand photosynthesis as a natural solar energy process and its role in sustainable design. - Analyze how bio-inspired solar technologies mimic plant-based energy conversion. - Engage in problem-solving and innovation using bio-design principles. - Develop AR-based prototyping skills to visualize energy-efficient solar designs. - Apply STEM concepts to address real-world energy challenges.





<p>Resources and didactic tools used</p>	<p>- Scientific Papers & Books on Photosynthesis and Bio-Inspired Solar Technology. - AR Applications (e.g., McGraw Hill AR, PhotosynthesisVR, CoSpaces Edu, Assemblr EDU, Merge Cube) for interactive learning.</p>
<p>Evaluation criteria and assessment</p>	<p>Assessment will be based on: - Concept mastery through interactive quizzes and discussions. - Hands-on AR-based assessments: Simulations and prototyping exercises using AR tools. - Creative project design: Students will propose and present a bio-inspired solar panel concept using AR visualization. - Feedback & Reflection: Students will evaluate the effectiveness of bio-inspired solar technology in addressing sustainability challenges.</p>

Introduction

Plants are nature's green factories, converting sunlight into chemical energy through the process of photosynthesis. This remarkable natural mechanism not only sustains life on Earth but also serves as an inspiration for cutting-edge solar energy technologies. By studying how plants efficiently capture and utilize solar energy, scientists have developed bio-inspired designs that improve the performance of solar cells. This training unit introduces students to the fascinating connection between photosynthesis and renewable energy, emphasizing how augmented reality (AR) can enhance their understanding of these concepts.

Photosynthesis is the process by which plants use sunlight to produce glucose, a form of stored chemical energy, while releasing oxygen as a byproduct. This process occurs in two stages: the light-dependent reactions and the Calvin cycle. In the light-dependent reactions, chlorophyll absorbs sunlight, splitting water molecules into oxygen, protons, and electrons. The energy generated in this stage is stored in molecules like ATP and NADPH, which are later used in the Calvin cycle to synthesize sugars from carbon dioxide(https://www.uaex.uada.edu/farm-ranch/special-programs/Education_in_Agriculture/soybean-science/GRC%20Photosynthesis%20lesson-final.pdf)(<https://opentextbc.ca/biology/chapter/5-1-overview-of-photosynthesis/>).

Inspired by this efficient energy conversion system, researchers have developed innovative technologies such as bio-inspired photovoltaic (PV) systems. For instance, the "PV-leaf" mimics plant transpiration to cool solar cells, improving energy efficiency and reducing heat loss (<https://innovationorigins.com/en/a-big-leap-in-solar-power-the-bio-inspired-photovoltaic-leaf-shows-greater-efficiency/>). Similarly, perovskite solar cells have been enhanced using biomimetic techniques that replicate natural lipid membranes to protect against environmental degradation while maintaining high efficiency(<https://techxplore.com/news/2023-08-bio-inspired-solar-devices-boost-stability.html>)(<https://list.solar/news/bio-inspired-1/>)





Augmented reality offers a unique way to visualize these processes. AR applications allow students to explore photosynthesis at a molecular level, observing how light excites chlorophyll molecules or how electrons travel through the thylakoid membrane. These tools make abstract scientific concepts tangible and engaging, fostering a deeper understanding of the link between biology and renewable energy technologies (https://stileapp.com/static/CLL%20handouts/Lesson_035_handout.pdf) (<https://sinovoltaics.com/technology/solar-fuels-an-introduction-to-artificial-photosynthesis/>)

By examining how plants harvest solar energy and applying these principles to human-made systems, students will gain insight into sustainable energy solutions. This unit not only highlights the importance of interdisciplinary learning in STEM but also encourages students to think creatively about solving real-world problems using nature as a guide.

How plants harvest solar energy

Nature serves as a rich and dynamic source of inspiration for material innovations, paving the way for the creation of new materials known as "bioinspired materials." These materials exhibit improved structural and functional characteristics derived from existing compositions and substances (Liu et al., 2017). The concept of "bioinspiration" stems from the approach of drawing insights from natural structures and functionalities to engineer advanced artificial materials with superior properties (Zhang et al., 2024).

The biological sources of inspiration, whether from the plant or animal kingdom, provide the foundation for developing artificial materials that replicate or are influenced by their properties and functions (Zhang et al., 2020). Numerous biological structures have been investigated for their potential in bioinspired material design, including nacre, spider silk, lotus leaves, fly eyes, and butterfly wings (Sun et al., 2019). Plants, which first emerged approximately 400 million years ago, have undergone significant evolutionary advancements to adapt and thrive in harsh environments (Pires and Dolan, 2012). Despite their limited fundamental building blocks, plants exhibit remarkable structural and functional diversity, which has inspired the development of high-performance surfaces and interfaces, such as the Nepenthes-inspired directional liquid transport mechanism (Chen et al., 2016).

Furthermore, the integration of plant-inspired materials and structures has significantly improved the efficiency of various technologies, including energy harvesting, conversion, and storage systems, as well as water desalination and purification devices, separation and collection mechanisms, and structural reinforcement and toughening solutions (Yu et al., 2024).



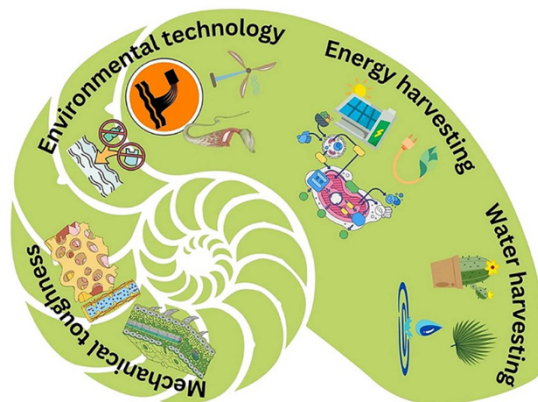
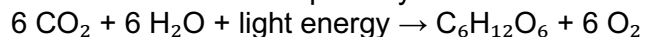


Figure 1. Graphical illustration of plant-inspired surfaces and interfaces for various applications, source: Wijerathne et al., 2025.

Photosynthesis is a complex process by which plants, algae, and some bacteria convert light energy into chemical energy. This process is fundamental to life on Earth, providing the energy and organic compounds that sustain most ecosystems.

The overall reaction of photosynthesis can be summarized by the following equation:



In this process, carbon dioxide and water are converted into glucose and oxygen using sunlight as the energy source (<https://www.britannica.com/science/photosynthesis>)

The process of photosynthesis is crucial for life on Earth. It produces oxygen as a byproduct, which is essential for most living organisms. Additionally, the organic compounds created through photosynthesis form the base of most food chains.

Photosynthesis is carried out by photoautotrophs, organisms that can produce their own food using light energy. These include plants, algae, and some bacteria

Understanding photosynthesis is not only important for biology but also for addressing global challenges. The fossil fuels we use today are the result of photosynthesis that occurred millions of years ago. Moreover, research into artificial photosynthesis could lead to new sustainable energy technologies (<https://www.britannica.com/science/photosynthesis>).

Plants, algae, and some bacteria have mastered the art of harnessing sunlight to sustain life on Earth. This process, called photosynthesis, enables them to convert solar energy into chemical energy, producing the oxygen we breathe and the food we eat. Understanding how plants efficiently capture and store energy can inspire sustainable solutions for human energy needs.





How Does Photosynthesis Work?

Photosynthesis takes place inside chloroplasts, specialized structures in plant cells. These contain chlorophyll, the green pigment that absorbs sunlight. Using light, water, and carbon dioxide, plants produce glucose (a sugar used for energy) and oxygen (released into the air).

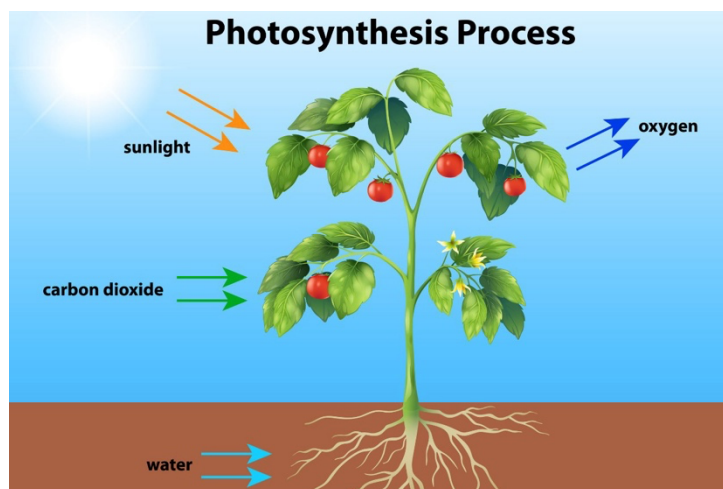


Figure 2. Process of photosynthesis, source:

<https://dotandlinelearning.com/blog/biology/chapter-6-photosynthesis/>

The process occurs in two main stages:

Stage 1: Capturing Light Energy (Light-Dependent Reactions)

- Takes place in the thylakoid membranes of chloroplasts.
- Sunlight is absorbed by chlorophyll, exciting electrons and starting an energy transfer process.
- Water molecules are split into oxygen, protons, and electrons, releasing oxygen gas into the atmosphere.
- The energy captured is stored in special molecules called ATP (adenosine triphosphate) and NADPH (nicotinamide adenine dinucleotide phosphate), which will be used in the next stage.

Stage 2: Producing Energy (The Calvin Cycle)

- Occurs in the stroma, the fluid inside chloroplasts.
- Carbon dioxide from the air is used to build glucose molecules.





- The ATP and NADPH from the first stage provide the energy to convert carbon dioxide into sugars.
- This stored energy is used for plant growth, reproduction, and the production of essential materials like starch and cellulose.

Why is Photosynthesis Essential?

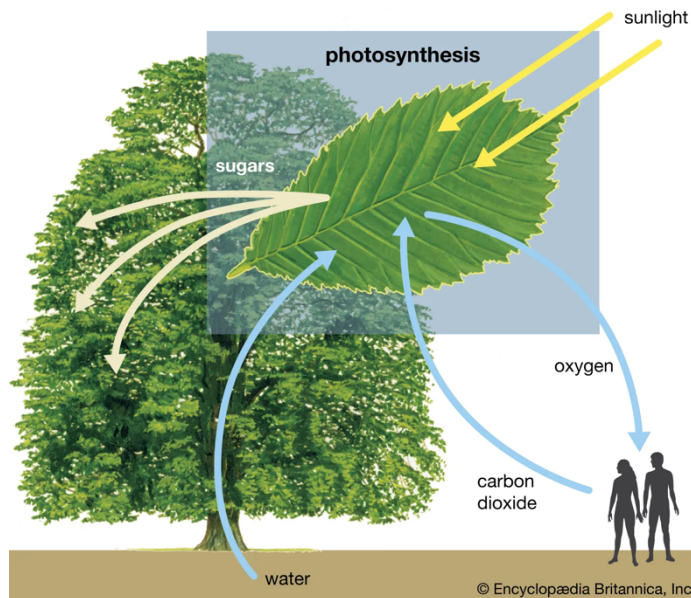


Figure 3. Photosynthesis essential, source: <https://www.britannica.com/science/photosynthesis>

Photosynthesis is the foundation of life on Earth, supporting ecosystems and maintaining environmental balance. Its key contributions include:

- **Oxygen Production:** Plants release oxygen, making life possible for animals and humans.
- **Energy Storage:** Sunlight is converted into chemical energy, which supports plant growth and provides food for other organisms.
- **Carbon Cycle Balance:** Photosynthesis helps regulate atmospheric carbon dioxide, reducing the effects of climate change.

Learning from Plants: How Photosynthesis Inspires Renewable Energy

The ability of plants to efficiently capture sunlight has inspired technological advancements in sustainable energy. Scientists are studying photosynthesis to develop artificial photosynthesis systems that mimic plant energy production, potentially leading to clean energy solutions such as:

- **Solar Panels:** Photovoltaic cells in solar panels work like chlorophyll, absorbing light and converting it into usable energy.
- **Biofuels:** Some microorganisms use photosynthesis to create fuels that could replace fossil fuels.
- **Artificial Leaves:** Scientists are developing synthetic materials that can use sunlight to produce clean energy, just like real leaves.





Nature has perfected solar energy conversion through photosynthesis, a process that sustains life and balances our environment. By studying plants, scientists and engineers are unlocking new ways to harvest energy sustainably. If we can learn to capture sunlight as efficiently as plants, we may move closer to a cleaner, greener future.

Photosynthetic Efficiency

Photosynthetic efficiency refers to how effectively plants convert solar energy into chemical energy. While theoretical maximum efficiency is approximately 11% under ideal conditions, real-world efficiency ranges between 3–6% due to factors like light absorption limits and energy losses during conversion processes (<https://www.britannica.com/science/photosynthesis/Energy-efficiency-of-photosynthesis>). For example:

- Only photons within the 400–700 nm range are usable.
- Energy losses occur during electron transport and sugar synthesis.

Bio-Inspired Solar Technology

Bio-inspired solar technology, also known as biological photovoltaics, is a cutting-edge field that draws inspiration from nature's ability to capture and convert sunlight into usable energy. The process of photosynthesis, which has evolved over billions of years, remains one of the most efficient energy conversion mechanisms in existence. By mimicking natural photosynthetic systems, scientists and engineers aim to develop highly efficient, sustainable, and cost-effective solar energy solutions that can help transition the world toward clean, renewable energy sources.



With the rising demand for sustainable energy solutions, traditional photovoltaic (PV) technologies, while effective, have limitations, such as high production costs, material scarcity, and efficiency constraints. Researchers are now looking toward nature for solutions, developing biohybrid solar cells, artificial photosynthesis systems, and biological photovoltaic platforms that use natural or bio-inspired components to improve solar energy conversion. This approach not only seeks to enhance the efficiency and stability of solar panels but also promotes eco-friendly production methods that minimize waste and reliance on rare materials.





How Nature Inspires Solar Innovation?

Photosynthesis in plants, algae, and certain bacteria provides a blueprint for the next generation of solar energy technologies. At its core, photosynthesis efficiently absorbs sunlight, splits water molecules to produce oxygen, and converts carbon dioxide into energy-rich compounds like glucose. Scientists are working to replicate and improve upon these processes using materials that mimic chlorophyll, electron transport chains, and carbon-fixation reactions to generate electrical energy and synthetic fuels.

There are several strategies in bio-inspired solar technology currently being explored:

1. **Biohybrid Solar Cells:**
These solar cells integrate biological component, such as photosynthetic proteins (Photosystem I and Photosystem II), with synthetic materials, improving light absorption and energy transfer. Researchers have successfully extracted photosynthetic proteins from plants like spinach to create solar devices that enhance energy conversion efficiency (https://en.wikipedia.org/wiki/Biohybrid_solar_cell?utm).
2. **Biological Photovoltaics (BPV):**
BPVs utilize living organisms, such as cyanobacteria or algae, to harvest sunlight and generate electrical current. These systems take advantage of the self-repairing and self-sustaining properties of biological materials, offering a low-cost and sustainable alternative to traditional silicon-based solar cells (https://en.wikipedia.org/wiki/Biological_photovoltaics?utm).
3. **Artificial Photosynthesis Systems:**
Artificial photosynthesis seeks to recreate nature's ability to convert sunlight, water, and carbon dioxide into fuel. Technologies like the Bionic Leaf, developed by Harvard researchers, use catalysts to split water molecules into hydrogen and oxygen, then combine CO₂ with bacteria to create liquid fuels. These systems have achieved higher efficiency than natural photosynthesis, making them a promising solution for clean fuel production (https://en.wikipedia.org/wiki/Bionic_Leaf?utm).
4. **Self-Cleaning and Self-Repairing Solar Panels:**
Plants have evolved self-repair mechanisms that allow them to restore damaged photosynthetic proteins over time. Inspired by this, researchers are developing solar panels with self-healing capabilities, using light-responsive polymers and photoactive coatings that mimic natural repair processes. These innovations prolong solar panel lifespan and maintain efficiency over time.
5. **Tunable Light Absorption Inspired by Leaves:**
Unlike conventional solar panels, which can be inefficient under changing light conditions, plants have evolved adaptive mechanisms that allow them to adjust their light-harvesting efficiency based on environmental conditions. Inspired by this, engineers are designing dynamic solar panels that adjust their absorption rate depending on the time of day and intensity of sunlight, mimicking the natural movement of leaves and chloroplast structures (<https://www.axios.com/sponsored/the-technology-paving-the-way-for-the-future-of-solar-energy?utm>).





Recent Advances and Applications:

- **Biomimicry in Design:** Innovators are increasingly looking to nature for sustainable solutions. For instance, the design of Japan's 500-series Shinkansen bullet train was inspired by the kingfisher bird, resulting in enhanced efficiency and reduced noise. This principle of biomimicry is being applied across various fields, including solar technology, to develop systems that harmonize with natural processes (<https://www.reuters.com/sustainability/land-use-biodiversity/bullet-trains-green-buildings-innovators-take-cue-nature-through-biomimicry-2025-01-13/>).
- **Perovskite-Silicon Tandem Cells:** Companies like Qcells have achieved breakthroughs by combining perovskite materials with traditional silicon solar cells, setting new records in efficiency. This advancement could lead to more compact and efficient solar panels, addressing space constraints in solar installations (<https://www.reuters.com/business/energy/qcells-says-technology-breakthrough-could-reduce-space-needed-solar-panels-2024-12-18/>).
- **Solar Paint for Electric Vehicles:** Innovations such as solar paint are being developed to enable electric vehicles to harness solar energy directly, potentially reducing reliance on external charging infrastructure and alleviating range anxiety among users (<https://www.thetimes.com/uk/technology-uk/article/mercedes-benz-solar-paint-charge-evs-rcp86z8hd?region=global>)

From Leaves to Solar Cells: Biomimetic Approaches to Sustainable Energy

The urgent need for sustainable and eco-friendly energy conversion technologies continues to rise as the world seeks effective solutions to combat environmental challenges and achieve net-zero emissions by 2050. Nature, particularly plants, offers a highly efficient model for solar energy harvesting, carbon dioxide absorption and conversion, and rapid electrolyte transport through their biological structures. These natural processes have inspired scientists to develop materials and devices that replicate the structural and functional characteristics of plant tissues and cells. Innovations based on plant-inspired materials have been successfully integrated into various areas of sustainable energy technologies. For instance, in the field of solar energy, bio-inspired materials have contributed to the advancement of solar cells and photovoltaic devices, significantly improving their ability to absorb sunlight and convert it into electricity with higher efficiency. By mimicking the efficiency of natural photosynthesis and transport systems, these technologies are paving the way for more effective and environmentally friendly energy solutions. By studying the process of photosynthesis in plants, photocatalytic devices for converting captured CO₂ into biofuels, such as ethanol, starch and other hydrogen carbonate fuels under solar irradiation have been innovated. Different from direct solar energy harvesting and conversion processes, plant-inspired energy generation has been remarkably integrated with kinetic and mechanical energy. Plant-inspired hydrovoltage devices convert water diffusion energy into electricity by learning from the water diffusion gradient effect of plants. By taking inspiration from the nanofluidic transport properties and selective cell structures, bioinspired materials have been developed for advanced energy storage devices for real-world scenarios, such as batteries and supercapacitors. For instance, increased ion conductivity and water retention were observed in solid-state electrolytes incorporated with natural bamboo cellulose nanofibers, which enhanced the electrochemical performance of the flexible Zn-air battery (Du et al., 2024). A plant-like battery (FlowER: an evaporation flow redox) with prolonged battery life was eco-designed to power the wireless sensor networks for aiding precision in agriculture (Navarro-





Segarra,2022). Similar plant- inspired designs have also been applied to other active metal-based batteries, including zinc-ion batteries (Zhang, et al., 2024, Dong et al., 2023). To show- case how bioinspiration paves the way to further enhancing the performance of sustainable energy technologies, we categorize plant-inspired materials in terms of the types of emerging technologies.

Plant-Inspired Innovations in Solar Energy Collection and Transformation

The primary challenges in harvesting and converting solar energy into electricity or other sustainable energy sources lie in the efficient absorption of solar radiation and the effectiveness of energy conversion. Solar cells represent a well-established category of sustainable energy conversion devices that directly transform solar radiation into electricity. These devices have been widely adopted and installed in various locations around the world.

The efficiency of solar cells has reached a limit that requires significant improvement, as more than 70% of the incoming energy is lost as waste heat. This not only reduces overall efficiency but also raises safety concerns. Inspired by trees, which efficiently transport water from the roots to the leaves through transpiration to maintain cooling and hydration, a bioinspired hybrid multigeneration photovoltaic-leaf (PV-leaf) was developed. This design enables passive water flow from a reservoir to the cell surface for evaporation, while also capturing the evaporated water and converting it into clean water (Wijerathne et al., 2025).

- Photovoltaic Leaf (PV-Leaf)

Over billions of years of evolution, natural organisms have developed highly efficient methods for collecting solar energy and storing it as hydrocarbons, such as sugar and starch, to sustain growth and survival. Research has shown that plant leaves contain light-harvesting antenna structures, known as chloroplasts, which enable the absorption of a broad spectrum of sunlight. These structures also function as long-range channels that transfer excitons from the excited electronic states of chlorophyll, following photon absorption, to the reaction centers where photosynthesis takes place(Mirkovic et al., 2017).

Within a natural leaf, interconnected three-dimensional porous and channel networks are present, optimizing light absorption and facilitating the movement of essential substances. Inspired by these structures and the mechanisms of natural photosynthesis, researchers have extensively developed artificial solar-to-fuel conversion processes, enabling the transformation of carbon dioxide into multi-carbon products, as well as solar-driven hydrogen generation (Liu et al., 2021).

By replicating the structure of chlorophyll and the functional processes of photosynthesis in plant leaves, artificial leaves have been developed to enable bioinspired solar energy harvesting and conversion (Van Noorden, 2021, Reece et al., 2011, Nguyen et al., 2017).

To enhance gas diffusion and light-harvesting efficiency, three-dimensional artificial photosynthetic systems are often designed with a hierarchical electrode structure similar to that of a natural leaf. For instance, artificial leaves have been developed using synthetic nanomaterials embedded within plant-derived frameworks, forming bio-hybrid systems (Zhou, 2013) .





The PV-leaf mimics the transpiration process in plant leaves to cool solar cells, improving their efficiency. This design incorporates a biomimetic transpiration layer made of bamboo fibers and hydrogel cells that passively move water from a reservoir to cool the solar panel surface. By reducing operating temperatures by up to 26°C, the PV-leaf enhances electrical efficiency and can simultaneously generate electricity, heat, and clean water.

During the synthesis process, the leaf's natural architecture and venation systems were directly replicated and incorporated into the artificial photosynthetic system, creating a three-dimensional hierarchical macropore network. These artificial leaves, constructed with man-made catalysts, effectively capture light and facilitate carbon dioxide photoreduction, mimicking natural photochemical processes to convert carbon dioxide and water into high-value hydrocarbons under natural or simulated sunlight. Beyond bioinspired devices for carbon dioxide capture and conversion, research over the past decade has explored solar water splitting using leaf-inspired structures. As a clean energy source with no carbon emissions, hydrogen is expected to play a crucial role in future energy systems, particularly when generated through water-splitting reactions. The concept of hydrogen production through water splitting has also been influenced by the natural mechanisms of photosynthesis (Velasco-Garcia and Casadevall, 2023).

The structure of a typical plant leaf consists of photosynthetic cells, vascular bundles (veins), sponge cells, stomata, the cuticle, and the epidermis, as shown in Figure 1a. Water transport within the plant occurs through a process driven by capillary forces and osmotic pressure, enabling the movement of liquid water from the soil to the leaves. The vascular bundles contain microchannels that efficiently distribute water throughout the leaf, which then evaporates from cell surfaces during transpiration.

Inspired by the efficiency of transpiration and the structural design of natural leaves, a biomimetic transpiration structure has been developed for the PV-leaf, as depicted in Figure 1b. This design integrates a biomimetic transpiration (BT) layer attached to the back of a solar PV cell, enhancing heat dissipation. The function of vascular bundles is replicated using natural bamboo fiber bundles, ensuring effective water transport and distribution. Meanwhile, hydrogel cells with a high specific surface area and superior water absorption properties serve as a substitute for sponge cells, promoting efficient evaporation.

A detailed configuration of the PV-leaf transpiration structure is shown in Figure 1c, comprising a BT layer (~1 mm thick), a supporting mesh (0.5 mm thick), and a PV cell layer (~150 μm thick), covering an effective area of 10 × 10 cm². Embedded within the BT layer are approximately 30 branches of bamboo fiber bundles, uniformly distributed within a potassium polyacrylate (PAAK) superabsorbent polymer (SAP) hydrogel, which facilitates even water distribution across the layer. The fiber branch ends are gathered and submerged in water, maintaining continuous hydration.

The step-by-step fabrication process for the PV-leaf transpiration structure is presented in Supplementary Figure 1, while Supplementary Figure 2 provides a circuit diagram detailing the electrical measurement system used for performance evaluation (Huang et al., 2023).



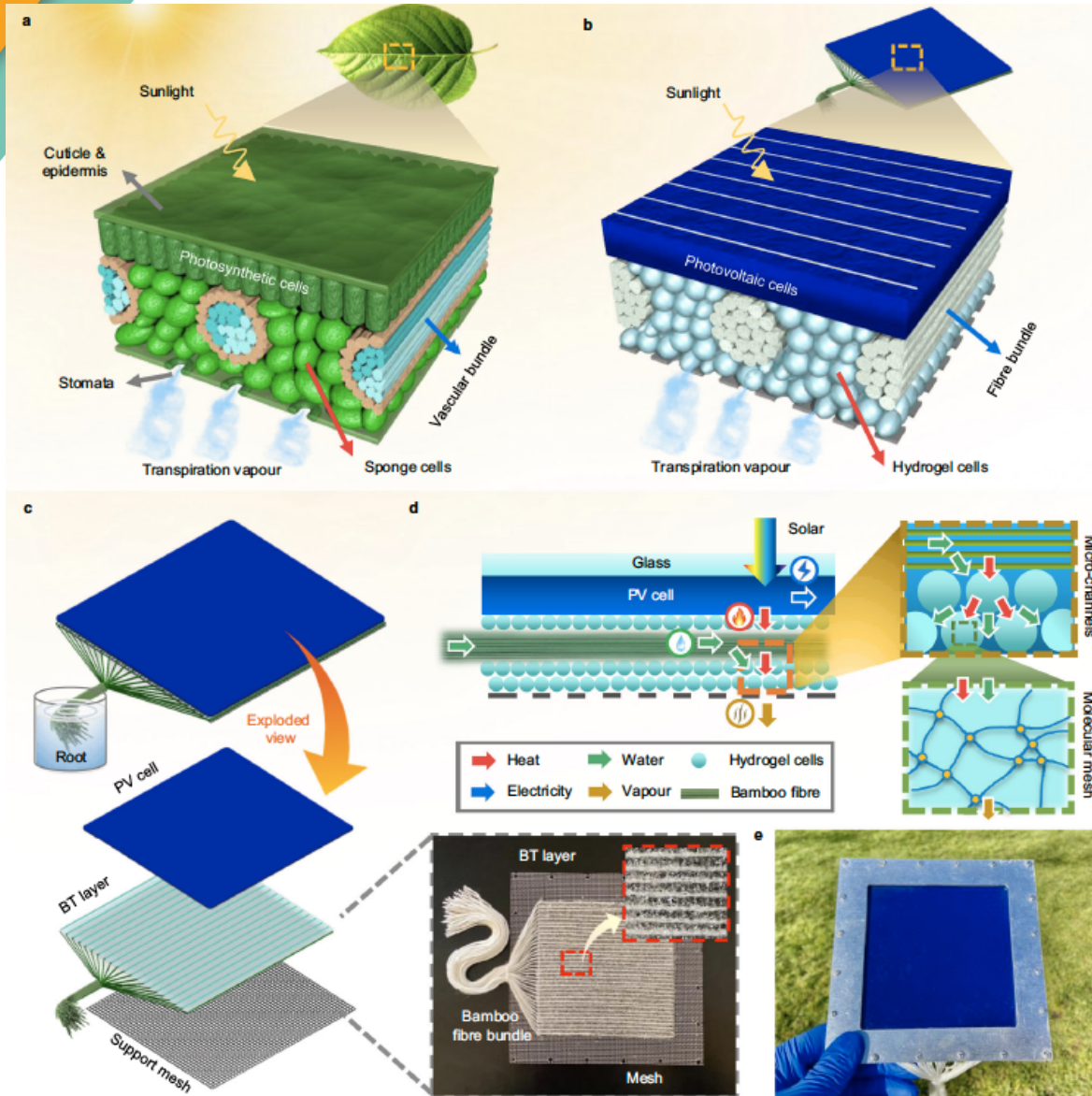


Figure 4. Structure and Function of the Bio-Inspired PV-Leaf, a. A natural leaf has vascular bundles that evenly distribute water across its surface, allowing for cooling through transpiration, which protects photosynthesis. b. The bio-inspired PV-leaf mimics this process using hydrophilic fiber bundles and hydrogel cells to replicate the water transport and storage functions of a real leaf. c. The biomimetic transpiration (BT) layer is made of bamboo fiber bundles and hydrogel cells, with the fiber roots placed in water for continuous moisture supply. d. Water moves from the fiber roots to the hydrogel cells through capillary action and osmosis. As water evaporates, it





removes heat from the PV cell, keeping it cool. e. A real-life photograph of the PV-leaf prototype shows how this bio-inspired structure is applied to a working solar cell (Huang et al., 2023).

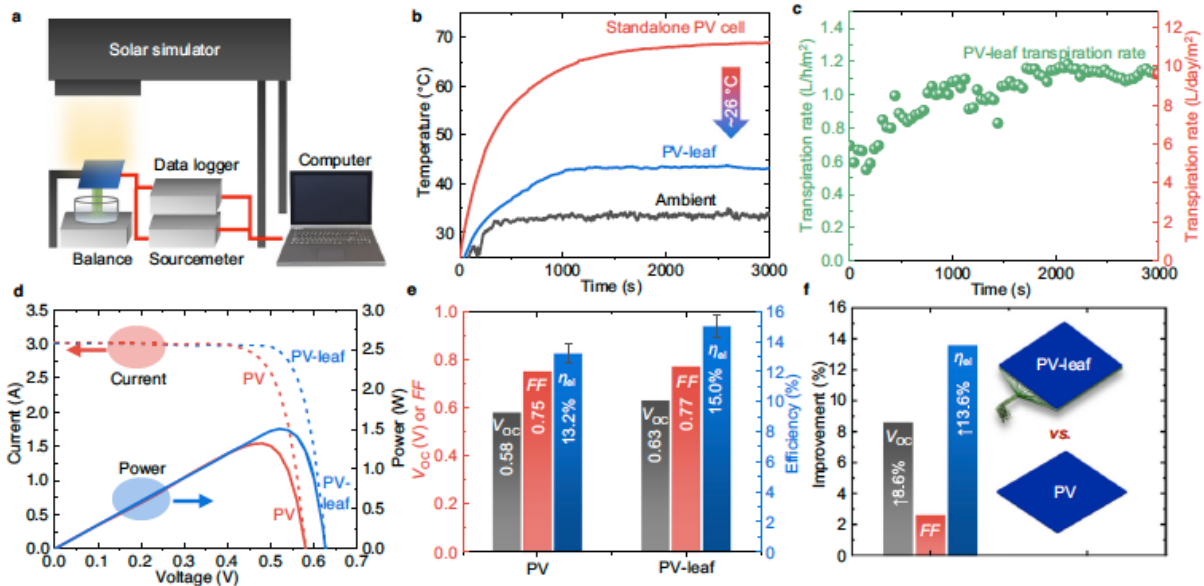


Figure 5. How the PV-Leaf Improves Solar Panel Performance, a. To test how well the PV-leaf works, a special setup was created using a solar simulator that produces light similar to sunlight. This setup helps measure the cooling effect and energy efficiency of the PV-leaf compared to a regular solar panel. b. The PV-leaf stays much cooler than a conventional solar panel. Tests showed that the biomimetic transpiration layer helps lower its temperature significantly, preventing overheating and improving performance. c. The PV-leaf releases water through transpiration, just like a real leaf. This process helps remove heat from the solar panel, making it more efficient. The amount of water evaporated over time shows how well the cooling system works. d. The PV-leaf produces more energy than a standard solar panel. The improved cooling system helps the solar cells generate higher power output, making them more effective in capturing and using sunlight. e. Key measurements show that the PV-leaf performs better in terms of energy production and efficiency compared to a regular solar panel. f. Overall, the PV-leaf improves solar energy conversion by keeping the panel cool and ensuring higher efficiency throughout the day. This bio-inspired design can help make solar panels more effective and sustainable in the future (Huang et al., 2023).

Factors Affecting Photosynthesis and Their Role in Bio-Inspired Solar Technology

Photosynthesis is a complex biochemical process influenced by various environmental and physiological factors. These factors determine the rate at which plants convert light energy into chemical energy, directly impacting plant growth, carbon absorption, and oxygen production.





Understanding these factors not only helps improve agricultural efficiency but also guides the development of artificial photosynthesis systems and bio-inspired solar technology.

1. Light Intensity: The Power of Sunlight

Light is the driving force behind photosynthesis. The greater the light intensity, the more energy is available to excite electrons in chlorophyll, leading to an increase in the rate of photosynthesis. However, there is a saturation point beyond which additional light does not further enhance the process, as the plant's biochemical machinery cannot process the extra energy efficiently.

- Low Light Conditions (e.g., shaded environments or deep-sea algae) slow down photosynthesis due to insufficient photon availability.
- Too Much Light can lead to photoinhibition, where excess light damages the photosynthetic pigments and reduces efficiency.
- Bio-Inspired Solar Connection: Engineers designing solar panels and artificial photosynthesis systems study how plants optimize light absorption. Some researchers are developing adaptive solar panels that mimic the ability of leaves to adjust their orientation for maximum sunlight exposure (https://www.rsb.org.uk/images/15_Photosynthesis.pdf).

2. Carbon Dioxide Concentration: Fuel for Carbon Fixation

Carbon dioxide (CO₂) is essential for the Calvin cycle, where it is converted into glucose. The higher the CO₂ concentration, the faster the rate of carbon fixation—up to a certain limit. However, at very high concentrations, the effect levels off due to limitations in enzyme activity and energy supply.

- Limiting CO₂ Levels: In low-CO₂ environments, photosynthesis slows down because plants cannot efficiently generate sugars.
- Industrial and Urban Impact: Increased CO₂ levels from human activities enhance photosynthesis but may also lead to climate imbalances affecting plant growth.
- Bio-Inspired Solar Connection: Scientists are exploring ways to capture and utilize CO₂ efficiently in artificial photosynthesis, developing systems that convert atmospheric CO₂ into sustainable fuels (Wang et al., 2022).

3. Temperature: The Role of Enzymes in Energy Conversion

Temperature significantly influences photosynthesis because it affects enzyme activity, particularly RuBisCO, the enzyme responsible for carbon fixation.

- Optimal Temperature Ranges: Photosynthesis typically peaks within a moderate temperature range (15–30°C). Below this range, enzyme activity slows, and at higher temperatures, enzymes denature, leading to reduced efficiency.
- Extreme Heat and Water Loss: High temperatures also cause excessive transpiration, reducing water availability, which is crucial for photosynthesis.
- Bio-Inspired Solar Connection: Artificial photosynthesis systems must be thermally stable, ensuring efficient energy conversion across varying temperature conditions. Scientists are exploring heat-resistant catalysts that mimic the temperature tolerance of desert plants.





4. Water Availability: Essential for Photosynthetic Reactions

Water is split during the light-dependent reactions of photosynthesis, providing electrons and protons needed for energy production. Limited water availability slows down or stops photosynthesis, causing stomatal closure to conserve moisture but also reducing CO₂ uptake.

- **Drought Conditions:** Plants in arid environments have evolved specialized mechanisms, such as Crassulacean Acid Metabolism (CAM) photosynthesis, to conserve water while still performing photosynthesis.
- **Bio-Inspired Solar Connection:** Scientists are developing water-efficient artificial photosynthesis systems that function effectively even in low-humidity environments, mimicking desert plant adaptations.

5. Wavelength and Quality of Light: Beyond Just Brightness

Not all light is equally effective for photosynthesis. Chlorophyll primarily absorbs red and blue light, with minimal absorption in the green range, which is why leaves appear green.

- **Artificial Light Sources:** LED technology is now used in controlled farming environments to optimize plant growth by providing the most efficient wavelengths.
- **Bio-Inspired Solar Connection:** Research into light-harvesting materials inspired by photosynthetic antenna complexes aims to improve solar cell efficiency, capturing a broader spectrum of sunlight for energy conversion.

Photosynthesis as a Model for Future Energy Solutions

Beyond sustaining life, photosynthesis serves as inspiration for artificial energy systems. Scientists are actively developing bio-inspired solar technology to replicate and enhance natural energy conversion mechanisms:

- **Artificial Photosynthesis:** Mimics the ability of plants to split water and store energy in chemical bonds, potentially producing clean hydrogen fuel.
- **Biohybrid Solar Cells:** Integrate natural proteins or pigments from plants into photovoltaic devices to increase efficiency.
- **Self-Repairing Solar Panels:** Inspired by the self-repairing nature of plant cells, researchers are developing materials that can fix damage from sun exposure, extending panel lifespan.

Understanding the factors affecting photosynthesis not only helps us appreciate plant efficiency but also guides future innovations in solar energy. By studying light absorption, CO₂ capture, temperature regulation, and energy storage in plants, scientists are making significant progress toward creating smarter, more efficient, and sustainable solar technologies.





Integrating Augmented Reality in Solar Leaves: How Plants Teach Us to Harvest Energy

1. Introduction: Enhancing Learning with Augmented Reality

Augmented Reality (AR) is transforming education by creating immersive and interactive learning environments that bridge the gap between theoretical knowledge and real-world application. In science education, AR allows students to visualize abstract concepts, interact with 3D simulations, and manipulate virtual objects that would otherwise be inaccessible in a traditional classroom setting.

With the increasing emphasis on STEM (Science, Technology, Engineering, and Mathematics) education, AR provides new opportunities for students to engage with complex scientific principles through experiential learning. Studies have shown that AR-based learning leads to higher retention rates and improved conceptual understanding compared to conventional teaching methods. The use of AR in science classrooms enhances spatial cognition, helping students grasp intricate biological and physical processes more effectively (Kaiwen and Wang, 2024).

In the context of solar energy and bio-inspired technology, AR serves as a valuable tool to demonstrate the principles of photosynthesis and explore how scientists replicate these natural processes in modern solar technology. The ability to visualize the mechanisms of light absorption, electron transfer, and energy storage through AR helps students connect biological efficiency with human-engineered solar technologies. This training unit integrates AR into the topic "Solar Leaves: How Plants Teach Us to Harvest Energy" to facilitate deeper understanding, foster curiosity, and inspire innovation in sustainable energy solutions.

2. Implementing AR in the "Solar Leaves" Training Unit

The integration of AR into this training unit follows a structured approach to enhance comprehension, engagement, and practical application of photosynthesis and bio-inspired solar technologies. By leveraging AR simulations, 3D models, and interactive experiences, students gain a first-hand perspective on how plants convert sunlight into energy and how scientists apply these principles to renewable energy development.

One of the primary AR applications used in this unit is McGraw Hill AR, which offers interactive 3D models that illustrate the structure of chloroplasts, the light-dependent and light-independent reactions of photosynthesis, and the molecular pathways involved in energy conversion. Students can manipulate these models to observe how sunlight is absorbed by chlorophyll, how electrons move through the electron transport chain, and how ATP and NADPH are synthesized. This hands-on interaction reinforces theoretical knowledge and allows students to see processes that would otherwise be invisible to the naked eye (McGraw Hill AR).

In addition to visualizing natural photosynthesis, AR helps students explore bio-inspired solar technologies, which seek to mimic the efficiency of plants in harvesting solar energy. Applications





such as PhotosynthesisVR allow students to experiment with artificial photosynthesis systems, simulate solar panel designs based on plant structures, and compare natural and synthetic energy conversion mechanisms. Through these simulations, students can assess the advantages of bio-inspired solar cells, such as their improved efficiency and ability to self-repair, similar to how leaves regenerate (<https://avrd.mediencampus.h-da.de/projekt/95635/?utm>).

Beyond existing AR tools, custom AR experiences can be developed using platforms like Unity AR Foundation, which allows educators to create interactive, curriculum-specific AR content. By using Unity-based AR applications, students can conduct virtual lab experiments where they adjust variables such as light intensity, wavelength, and temperature to observe how these factors influence photosynthesis and solar energy absorption. This enables personalized learning experiences, where students actively test hypotheses and analyze real-time data in a virtual environment.

Another key aspect of AR integration is its potential to enhance group collaboration and peer learning. By engaging with shared AR models, students can discuss observations, compare experimental outcomes, and collaboratively develop solutions to real-world challenges in renewable energy. The use of multiplayer AR experiences, where multiple students interact with the same virtual model in real-time, promotes teamwork, critical thinking, and problem-solving skills.

Despite its advantages, integrating AR into science education comes with challenges, such as technical accessibility, content quality, and learning adaptation. Not all students may have access to AR-compatible devices, and educators may require training on how to effectively implement AR tools in the curriculum. Additionally, high-quality AR applications that align with specific learning objectives are still being developed. Addressing these challenges involves providing device-sharing options, offering professional development programs for teachers, and selecting scientifically validated AR content (Kaiwen and Wang, 2024).

By carefully designing AR-based learning activities, this training unit ensures that students gain a holistic understanding of photosynthesis, bio-inspired solar technology, and the future of sustainable energy innovation.

Augmented Reality represents a transformative shift in the way students engage with scientific concepts, moving beyond passive learning toward interactive, exploratory experiences. By integrating AR into the Solar Leaves training unit, students not only learn about photosynthesis and solar energy conversion but also experience these processes in a way that deepens understanding and fosters innovation.

As the world transitions towards renewable energy solutions, the ability to mimic nature's efficiency in solar harvesting will play a crucial role in developing sustainable technologies. AR-based learning bridges the gap between biology and engineering, encouraging students to explore how scientific discoveries in nature can inform cutting-edge energy solutions. The use of AR stimulates curiosity, creativity, and problem-solving, which are essential skills for the next generation of scientists and engineers.

The continued advancement of AR technologies, artificial intelligence, and machine learning will further expand the potential for personalized, data-driven learning experiences. Future research may explore how real-time AR experiments, haptic feedback, and AI-driven simulations can create even more immersive educational environments, ensuring that students not only





understand science but actively participate in its evolution (https://www.reuters.com/sustainability/land-use-biodiversity/bullet-trains-green-buildings-innovators-take-cue-nature-through-biomimicry-2025-01-13/?utm_source=chatgpt.com).

By adopting AR as a core tool in science education, we prepare students for the future of interdisciplinary learning, where biology, technology, and sustainability converge. The integration of AR into this training unit provides a dynamic and forward-thinking approach to teaching solar energy, bio-inspired technology, and environmental science, equipping students with the knowledge and skills to tackle global energy challenges.

Execute and Enhance Example:

The integration of technology into education has transformed the way students engage with complex scientific concepts, making learning more interactive and accessible. Augmented Reality (AR) has emerged as a powerful educational tool that enhances traditional teaching methods by providing immersive, real-time interactions with digital content. Unlike Virtual Reality (VR), which creates entirely new environments, AR overlays digital information onto the real world, enabling learners to visualize abstract processes in a more tangible and engaging manner.

One of the most challenging biological concepts for young students to grasp is photosynthesis, the process by which plants convert sunlight into chemical energy. Traditional text-based and lecture-driven teaching approaches often struggle to make this concept clear and engaging, as students find it difficult to visualize molecular interactions and energy transformations. To address this, the use of AR-based mobile applications has gained traction as an innovative teaching method. These applications allow students to interact with 3D models of plants, observe animated photosynthesis processes, and manipulate variables to understand different environmental effects on plant energy conversion.

The educational benefits of AR in science learning have been widely recognized. Studies have shown that AR enhances comprehension by providing interactive visualizations that bridge the gap between theoretical knowledge and practical understanding. Prior research has demonstrated that AR applications improve student engagement and performance across various scientific disciplines, including mechanical design, mathematics, and astronomy. For instance, AR-supported teaching methods have been found to significantly enhance students' understanding of moon phases and mathematical analysis compared to conventional approaches.

In the context of photosynthesis education, AR technology can play a critical role in addressing conceptual challenges that students and even teachers face. Research has indicated that many educators are unaware of students' misconceptions about photosynthesis and often lack suitable experimental demonstrations to clarify these concepts effectively. Traditional lectures combined with hands-on activities, such as building physical models of chloroplasts, have been found to improve student engagement. However, AR takes this a step further by offering real-time interactive simulations, enabling students to visualize photosynthesis at both macroscopic and molecular levels.

To explore the effectiveness of AR-based learning, this study examines a specific educational exercise that utilizes an AR mobile application to teach photosynthesis to young students (see full





description in the attached document:
<https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=10645875>).

Overview of the Exercise

This educational exercise explores the use of augmented reality (AR) technology as an innovative tool to teach young students about photosynthesis. Traditional teaching methods, such as textbooks and lectures, often struggle to make this complex biological process engaging and comprehensible for students. The AR-based mobile application used in this exercise provides an interactive learning experience by allowing students to visualize photosynthesis in real time through 3D plant models and animations.

Unlike conventional methods, which rely heavily on static diagrams and verbal explanations, this AR application offers a dynamic and immersive experience, making abstract concepts more tangible. Through this digital approach, students can observe plant structures, simulate light absorption, and follow the transformation of solar energy into chemical energy in a highly interactive way. The exercise not only enhances conceptual understanding but also improves student engagement, motivation, and retention of scientific knowledge.

Implementation of the AR Exercise

1. Learning Objectives

The exercise aims to:

- Introduce students to the process of photosynthesis, emphasizing how plants convert sunlight into chemical energy.
- Improve visualization skills by using interactive 3D models to explore the role of different plant structures.
- Enable students to manipulate environmental variables, such as light intensity and carbon dioxide levels, to observe their effects on photosynthesis.
- Foster active learning and scientific inquiry by encouraging students to experiment, analyze, and draw conclusions.

2. AR-Based Learning Experience

The mobile AR application simulates key steps in the photosynthesis process and allows students to interact with digital plant models using their mobile devices or tablets. The exercise involves the following key features:

- **Plant Model Interaction:** Students can zoom in and rotate 3D plant models, focusing on key structures such as leaves, chloroplasts, and stomata. They can tap on different components to learn about their functions in photosynthesis.
- **Simulation of Light Absorption:** The application illustrates how chlorophyll absorbs light energy and initiates a sequence of reactions. Through animations, students can track the excitation of electrons and the splitting of water molecules, which releases oxygen.
- **Observation of the Photosynthesis Process:** A step-by-step animation guides students through the light-dependent reactions and the Calvin cycle, highlighting the





transformation of light energy into ATP and NADPH, and the subsequent conversion of carbon dioxide into glucose.

- Adjustable Environmental Factors: Students can modify light intensity, CO₂ levels, and temperature within the simulation to observe how these variables affect the rate of photosynthesis. This feature enables real-time experimentation, allowing learners to test hypotheses and analyze results.
- Assessment and Feedback Mechanism: The application includes built-in assessment tools, such as quizzes and interactive exercises, to track students' comprehension and learning progress. These assessments measure:
 - Understanding of key concepts (e.g., identifying reactants and products of photosynthesis).
 - Ability to analyze experimental data (e.g., predicting how changing light conditions impact oxygen production).
 - Engagement with the simulation (e.g., exploring different plant structures and their roles in energy conversion).

Comparison with Traditional Teaching Methods

One of the main challenges in traditional education is that students often struggle to visualize molecular processes that occur at microscopic levels. Textbooks and static diagrams provide only limited insight into the dynamic nature of photosynthesis. Moreover, lecture-based instruction often fails to actively engage students in hands-on learning.

In contrast, the AR-based approach enhances conceptual clarity by allowing students to interact with digital models, observe real-time simulations, and manipulate variables to see immediate results. The following table highlights the key differences:

Aspect	Traditional Teaching	AR-Based Learning
Visualization	Static diagrams and text	Interactive 3D models & animations
Student Engagement	Passive listening & reading	Active participation & real-time exploration
Experiments	Limited to classroom resources	Virtual simulations with adjustable conditions
Conceptual Understanding	May lead to misconceptions	Clear, interactive demonstrations
Assessment	Paper-based quizzes & tests	Integrated app-based quizzes & feedback

The AR exercise bridges the gap between theory and real-world application, making learning more immersive, flexible, and effective.

Benefits of the AR-Based Photosynthesis Exercise





The implementation of augmented reality in teaching photosynthesis offers several advantages:

1. **Enhanced Conceptual Clarity:** The interactive 3D models and animations make abstract biological processes easier to understand.
2. **Increased Student Engagement:** The hands-on, gamified learning experience encourages students to actively participate in scientific exploration.
3. **Real-Time Experimentation:** By modifying environmental factors, students can analyze cause-and-effect relationships in photosynthesis.
4. **Accessibility and Convenience:** The AR-based mobile application is portable and user-friendly, allowing students to learn at their own pace.
5. **Data-Driven Learning:** The built-in assessment tools provide instant feedback, helping teachers and students track progress effectively.

Phase	Description
Explore	- Research and Discovery: Investigate how natural photosynthesis works in plants and how it inspires solar technologies.
	- Content Development: Develop foundational materials about bio-inspired solar technology, photosynthesis, and AR integration.
	- Needs Analysis: Assess students' understanding of photosynthesis, solar energy, and STEM integration to tailor learning experiences.
Execute	- Curriculum Implementation: Deliver interactive lessons on solar energy inspired by plant biology using AR tools.
	- Interactive Exercises: Use AR applications (e.g., PhotosynthesisVR, McGraw Hill AR) for simulating photosynthesis and designing bio-inspired solar panels.
	- Feedback Collection: Gather student and teacher feedback on AR effectiveness and learning outcomes through discussions and reflections.
Enhance	- AR Integration: Embed AR simulations to visualize molecular photosynthesis processes and test solar panel efficiency.
	- Interactive Learning: Enable students to manipulate environmental factors like light intensity and CO ₂ concentration in AR.
	Gamified Content: - Points and Badges: Reward students for completing AR challenges (e.g., building a working solar panel prototype). - Leaderboards: Rank students or teams by their performance in energy efficiency simulations. - Quests and Levels: Design progressive challenges from basic photosynthesis to solar cell creation. - Rewards for Exploration: Hide energy facts or components in AR models to encourage deeper exploration. - Collaborative Gamified Tasks: Teams create and optimize virtual solar panels for maximum efficiency.
	AR-Based Assessments: -Include AR simulations and virtual labs as part of formative assessments to demonstrate understanding of solar conversion concepts.





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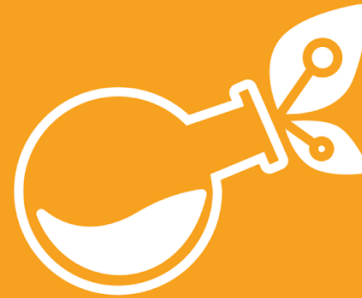
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BIO-INSPIRED STEM TOPICS FOR ENGAGING YOUNG GENERATIONS
THANKS TO THE USE OF AUGMENTED REALITY



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