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# Transformative Approaches to Elevate Hydrogen Production and Efficiency, Surpassing Microalgae-Bacterial Consortium (MABC) Technologies- A Review

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## Abstract

Microalgae represent an outstanding renewable resource for the sustainable production of biohydrogen, owing to their rapid growth rates, efficient carbon fixation, and adaptability to various aquatic environments, as well as their low nutritional demands and minimal land requirements. Nonetheless, their commercial viability is hindered by challenges such as low hydrogen yields and high production costs. Recent advancements have actively addressed these challenges by prioritizing the maximization of hydrogen yields through improved cultivation techniques, effective pretreatment strategies, and state-of-the-art integrated bioelectrochemical systems. This review provides a comprehensive analysis of the latest breakthroughs in biohydrogen production using microalgae, highlighting innovative pretreatment methods, significant progress in genetic engineering, efficient microbial immobilization techniques, and hybrid biohydrogen fermentation systems that significantly enhance hydrogen yields. Moreover, the review underscores the critical importance of advanced reactor designs, such as microbial electrolysis cells (MECs) and hybrid systems utilizing microalgae hydrolysate, which play a pivotal role in boosting biohydrogen production. Consequently, microalgae are positioned as a vital component in advancing a sustainable hydrogen economy. Beyond hydrogen production, algal biomass can assimilate nutrients and yield economic benefits through the generation of value-added products such as biodiesel, pigments, and various secondary metabolites. Additionally, the integration of microalgae in microbial fuel cells (MFCs) effectively mitigates greenhouse gas emissions and promotes carbon sequestration. Currently, microalgal-based wastewater treatment technology is gaining considerable attention as a green solution aligned with the principles of the circular bioeconomy. The capacity of microalgae to produce oxygen eliminates the necessity for external aeration processes, resulting in enhanced economic advantages. Photosynthetic MFCs emerge as a robust solution for integrating bioenergy production, pollutant removal, recovery of valuable byproducts, and effective wastewater treatment and management, all in alignment with the ambitious goals of a circular bioeconomy.

**Keywords: Pollutant Removal; Energy Utilization and Production; Product Recovery; Sustainable Development and Management**

## Micro-algae for Hydrogen Production: Biohydrogen Production from Microalgae Biomass

Hydrogen is emerging as a crucial alternative energy source that can fulfil global energy demands while addressing the depletion of fossil fuels and related environmental challenges. Microalgae-based biomass holds significant promise for hydrogen production due to its advantages as a green energy carrier and its carbon-free combustion. This review examines the processes involved in hydrogen production from microalgae, with a focus on cultivation techniques and the three primary conversion methods: thermochemical, photobiological, and electrochemical. The photobiological and electrochemical methods can produce pure hydrogen; they require further innovation to improve production rates, and high costs continue to pose a significant obstacle. To fully realize the potential of biohydrogen from microalgae, extensive research and collaborative efforts are essential to enhance its economic viability. Advancing this promising energy source is critical for a sustainable future.

Biohydrogen production from microalgae biomass represents a transformative opportunity that must be harnessed through three primary methods: thermochemical, biological, and electrochemical conversions.

1. Thermochemical Conversion: This method encompasses gasification, pyrolysis, and cracking, effectively converting biomass into valuable hydrogen.
2. Electrochemical Conversion: Utilizing electrolysis, this approach optimizes hydrogen production through advanced technological means.
3. Biological Conversion: Hydrogen synthesis can occur in both light and dark conditions via biophotolysis and dark fermentation.

Although current yields may limit commercial viability, the potential for growth in this area remains substantial (Singh et al., 2015). The research conducted by Ermis et al. (2022) highlights anaerobic liquid digestate (ALD) as a groundbreaking culture medium for microalgae, demonstrating superior performance compared to synthetic alternatives in terms of biomass yield and nutrient recovery. ALD effectively integrates anaerobic digestion with algae cultivation [10].

As we advance toward third-generation biohydrogen production, the role of machine learning technologies becomes increasingly critical. These tools enhance production efficiency by optimizing process control and predicting hydrogen outputs, thereby facilitating informed decision-making (Alagumalai et al., 2023). The successful implementation of machine learning in improving bio-oil production from microalgae (Ullah et al., 2023) and in generating hydrogen from sewage sludge (Aslam Khan et al., 2023) further underscores its importance. Embracing these innovative methodologies is essential for progressing sustainable energy initiatives. Biohydrogen is poised to emerge as a leading renewable energy solution, and now is the time to take decisive action [10].

The Green hydrogen is extensively observed as the ‘net zero’ fuel for the future energy system, with green oxygen replacing the related consumption of atmospheric oxygen hydrogen will be mandatory as a feedstock (example, for ammonia and methanol production) rather than as a fuel and some of the green oxygen will be applied to industrial processes and water oxygenation as different to existence expelled to the atmosphere (European State of the Climate, Glaciers and sea level rise, https://climate.copernicus.eu/ESOTC/2019/glaciers-and-sea-level-rise).

The energy is used in two forms (electrons and molecules), and it is now critical that both electricity and fuel are produced in an environmentally sustainable manner. If entirely present fossil fuel use were replaced with green hydrogen, the water requirement for electrolysis would amount to 1.8% of present global water consumption [6]. This new claim would be counterbalanced by water reserves attained by not having to produce fuels from petroleum or biomass and by decreasing the use of conventional thermal power plants. Besides, when green hydrogen is oxidised by combustion equipment and fuel cells, the same amount of water that was originally consumed by electrolysis is released back into the environment. Therefore, overall, a huge placement of electrolysis will have a relatively neutral impact on the global water resource. The electrolysers range from the decentralised hydrogen hubs at wastewater treatment plants to gigawatt-scale hydrogen production at offshore wind or solar farms. The annual water requirement of green hydrogen production relative to Earth’s water resources. The aeration of active sludge is the greatest life-threatening part of the energy-intensive wastewater treatment process, where microorganisms and oxygen work together to break down the organic matter.

The up-to-date research into microalgae as a clean energy source for hydrogen and methane production. The microalgae are a precise resource that could transform hydrogen production. The microalgae as a feedstock are prospective and attractive due to its high carbon dioxide fixation competence, growth rate, photosynthetic productivity, capability to grow in brackish water, which includes rivers and lakes, and also has the facility to cultivate it on land that is not suitable for agriculture. In contrast to agriculture or forestry-based biomass, microalgae are additional and appropriate for industrial-scale production for energy generation, which is easier to convert into hydrogen because of their simpler cellular structure. It could provide high revenue for microalgae cultivators, and microalgae cultivation has been limited for energy products since the main route for conversion has been biodiesel production, which has low value and market acceptability. Though hydrogen is extensively considered as the future fuel for large-scale commercial operations. The hydrogen production via renewable resources is essential to solve the energy crisis and bring down the global emissions from fossil fuels. At present, a vast majority of hydrogen comes from fossil fuels, which causes carbon dioxide emissions, leading to climate change. The hydrogen production through microalgae is potentially carbon-neutral. By means of microalgae, which can produce hydrogen that emits 36% less greenhouse gas emissions than current methods, with the possibility of this figure increasing to 87% with the incorporation of extra renewable energy progressions [17].

Among the algae, the Cyanobacteria (Blue-green algae) are promising micro-algae for hydrogen production. The bio-hydrogen from microalgae with cyanobacteria has gained attention in commercial awareness due to its potential as an alternative, reliable, and renewable energy source. The photosynthetic hydrogen production from microalgae (photosynthetic microbial fuel cells) can be a remarkable and favourable option for clean energy. The benefits are hydrogen evolution, which is separated from oxygen evolution; it can also produce relatively higher hydrogen yields, and the by-products can be efficiently converted to hydrogen. The bio-hydrogen from microalgae, including cyanobacteria, has attracted profitable cognizance due to its potential as an alternative, reliable, and renewable energy source. The photosynthetic hydrogen production from microalgae can be an exciting and promising route for clean energy. The microalgae have been used as feedstock for producing different value-added products, which include biodiesel, bioethanol, and biogas. Several microalgal species have been rummage-sale as feedstock for bio-hydrogen production. Among them, *Chlorella* sp., *Scenedesmus* sp., and *Saccharina* sp. have been extensively studied. The microalgae bio-hydrogen production technology predominantly includes fermentation bio-hydrogen production (e.g., photofermentation bio-hydrogen production, dark fermentation bio-hydrogen production, and photo-dark combined fermentation bio-hydrogen production) and photosynthesis bio-hydrogen production (e.g., direct biological photolysis bio-hydrogen production, indirect biological photolysis bio-hydrogen production) (Figure 1).

The Photobioreactor developments are being completed to produce microalgae in high concentration and low footprint. Hydrogen is a clean-burning fuel that only produces water vapour as a by-product of converting hydrogen into energy. Hence, the microalgae use this

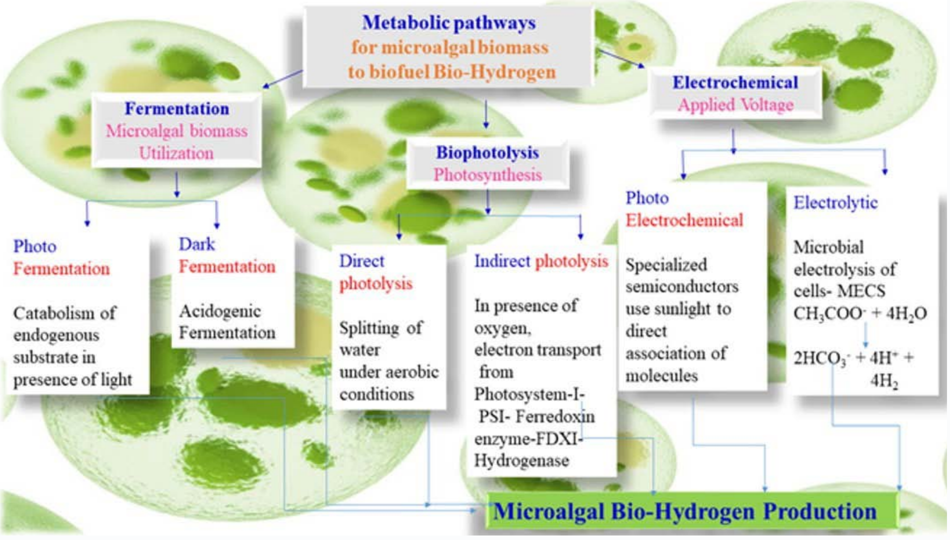

**Figure 1:** Potential pathways from microalgae to biofuels ($BioH_2$ Production) [41].

water (and $CO_2$ from the atmosphere) for their growth. Consequently, this process closes the carbon and hydrogen loop and is hence a highly sustainable technology.

## Strategies and Pathways for Biohydrogen Production for Improved Biohydrogen Production

Several approaches can be putative to progress bio-hydrogen ($bioH_2$) production using microalgae, such as immobilization of microalgae, pre-treatment techniques, nanoparticles, and genetic engineering. The pre-treatment instantly interrupts the microalgal cell walls and improves the availability of carbohydrates present in the cells. The different common pre-treatment methods are the following: chemical, thermal, mechanical, enzyme, and combined methods. The pre-eminent pre-treatment method and its optimal conditions are yet to be resolved [1, 2, 26-28]. The mechanism of immobilized microalgae is the entrapment of microalgal cells into or on a solid support. It has various benefits, such as high cell density, alleviating the manipulation of cultures, and relaxed microalgae cell harvesting. Additionally, this method protects the cells from unwanted contaminations and sudden changes in other culture parameters. This also results in high biohydrogen production due to the improved permeability of cell walls. Moreover, the microalgal cells wash out, are reduced, and cause a total increase in Hydrogen yields. The main interferences are the slow infusion of nutrients from the medium into microalgae and the high sunlight gradient within the cells because of high cell density [24]. The nanotechnology way of accomplishing $bioH_2$ production is due to its role in intracellular electron transfer, microalgae growth, and enzymes involved in $bioH_2$ generation. Genetic engineering and metabolic engineering can be used to modify specific pathways to increase $bioH_2$ production. The photosynthetic obstacles and constraining factors can be defeated (Li *et al*., 2022).

### The various steps involved in $bioH_2$ production

**Step 1: Algae Selection: species selection and its biological characteristics**

- Cyanobacteria
- Unicellular microalgae
- Multicellular microalgae

**Step 2: Select cultivation strategy- cultivation system**

- Open terrestrial systems
  - Phototrophic, mixotrophic
- Closed terrestrial systems
  - Phototrophic and mixotrophic, mixed-hybrid, heterotrophic
- Open offshore systems
  - Phototrophic

**Step 3: Harvest Algae and process algae into components**

- Harvesting
- Dewatering
- Fractionation
- Separation

**Step 4: Convert or upgrade components into biofuels and other products**

- Intermediate constituents
  - Hydrocarbons, Alcohols, Lipids,
  - Carbohydrates, Proteins, Consolidate biomass
- Conversion processes
  - Biochemical conversion, anaerobic digestion,
  - Thermochemical conversion, direct synthesis,
- Ends fuels and products
  - Renewable hydrocarbons,
  - Biodiesel, Biogas,
  - Alcohols, Co-products

### Algal Biomass to fuel pathways through different reactions

- Biochemical
- Anaerobic digestion- Biogas
- Alcoholic fermentation- Bioethanol
- Photo-biological hydrogen production (Bio-$H_2$)
- Photosynthetic
- Bioelectricity
- Thermochemical
- Direct combustion- Electricity
- Gasification-Syngas
- Lique faction-Bio-oil
- Pyrolysis- Bio-oil, Charcoal, Syngas.
- Transeterification
- Acid/Base Catalysis-Biodiesel
- Supercritical- Biodiesel

The transesterification process is a recognised process used to change crude oil into methyl ester. With the addition of a catalyst, the trans-esterification process has some successive reactions between vegetable oil and alcohol. Triglycerides are altered into monoglycerides during the trans-esterification process. The details of the biodiesel production process from microalgae have been described in a previous study [11]. Initially, preheated crude oil at 60 °C was added to the mixture of methanol (20% of the total crude oil) and sodium hydroxide (3.50 g) for one liter of oil. The mixture was kept for 8 hours in order to settle on the trans-esterification reaction reactor, and the glycerin was removed. The produced biodiesel was washed and filtered with appropriate techniques (Galadima and Murazaz, 2014). The production process of biodiesel flowchart is shown in Figure. It is essential to check the properties of the produced biodiesel before it is used in the engine. The essential fuel features of the produced biodiesel are described in the Table.

The Hydrogen production roadmap searches seven promising technology options for producing hydrogen. The expansion of clean, sustainable, and cost-competitive hydrogen production processes is vital to the market success of hydrogen-powered vehicles. The seven key manufacturing technologies fall into three wide categories: thermal, electrolytic, and photolytic processes (https://www1.eere.energy.gov/hydrogenandfuelcells/).

- One type of thermal process uses the energy stored in such resources as coal or biomass to simply release the hydrogen contained within their molecular structures. Other type uses heat in mixture with closed chemical cycles to yield hydrogen from feedstocks, such as water; these are known as “thermochemical” processes.
- Distributed Natural Gas Reforming Bio-Derived Liquids Reforming Coal and Biomass Gasification Thermochemical Production (Using a Heat-Driven Chemical Reaction to Split Water)
- In Electrolytic Processes, water electrolysis uses electricity to split water into hydrogen and oxygen. Hydrogen produced via electrolysis can result in Water Electrolysis (Splitting Water Using Electricity) with zero greenhouse gas emissions, depending on the source of the electricity used.

  In Water Electrolysis (Splitting Water Using Electricity), Photoelectrochemical Hydrogen Production (Using Solar Power to Directly Split Water) Biological Hydrogen Production (Photobiological Water Splitting)
- Photolytic methods convert light energy to split water into hydrogen and oxygen. Presently, in the very initial stages of research, these processes suggest long-term potential for sustainable hydrogen production with low environmental impact.

## Integration Approaches for $H_2$ Productivity Improvement

Hydrogen can be used as fuel for electricity generation, fuel for a hydrogen boiler for heating, and it can also be used to power fuel cells for transport and cogeneration for electricity and heat. The integration of the hydrogen system will affect the decarbonisation strategies of other energy sectors. A novel multi-energy systems optimisation model was proposed to exploit investment and functioning synergy in the electricity, heating, and transport sectors, considering the integration of a hydrogen system to diminish the overall costs. The model imitates two hydrogen production procedures, which comprise (i) the gas-to-gas (G2G) with carbon capture and storage (CCS), and (ii) power-to-gas (P2G). The grouping of the hydrogen system that alters the carbon emissions from the electricity system to other energy sectors in all the P2G, G2G, and OPT (joint process of P2G and G2G) scenarios [34].

The integration process of the hydrogen system will influence the decarbonisation strategies of other energy sectors. The combination of the hydrogen system shifts the carbon emissions from the electricity system to other energy sectors in all the P2G, G2G, and OPT scenarios. The decarbonisation of the heat sector under a 30 Mt carbon target will need a higher incorporation of low-carbon heat supply technologies (HP and HB) and amplified investment cost in the electricity and hydrogen sectors. When the carbon target is set strictly to 10 Mt, the undue hydrogen integration cost of P2G also increases the cost of decarbonisation in the electricity and heat sectors [34].

When additional economically hydrogen production approaches (G2G and OPT) are accepted to yield hydrogen, the penetration of hydrogen in the electricity and heat sectors increases further, and the carbon emissions of the whole system mainly come from the hydrogen system due to a higher share of hydrogen-fuelled power generation, and HB replaces most of the NGB [34].

The electricity–heat-transport–hydrogen economical ptimisation with environmental constraints at the national level, which simultaneously considers the infrastructure Energies 2020, 13, 1606 3 of 19 capital expenditures (CAPEX) and whole system operative expenditures (OPEX), thus assembling the specific carbon target at a lesser whole-system cost.

- It includes modelling of the hydrogen system into a joint optimization multi-energy systems model in view of both investment and operation at the system level.
- It assesses the system implications, economic, and environmental impact of different hydrogen production infrastructures across the whole system level.

**Table 1:** Showed Comparative overview of MABC.

| Technology | Major Advantage Over MABC | Main Limitation | Future Potential |
|---|---|---|---|
| Hybrid DF–PF | Very high substrate conversion | Light dependence in PF | Integrated waste biorefineries |
| MECs | High efficiency + wastewater treatment | Electrode cost | Decentralized hydrogen plants |
| Synthetic Biology | Tailored metabolic pathways | Regulatory complexity | Designer hydrogen microbes |
| PEC Water Splitting | High solar conversion efficiency | Material stability | Artificial photosynthesis |
| Thermochemical Systems | Industrial scalability | High energy demand | Large-scale green hydrogen |

- It also examines the impacts of hydrogen integration on each energy sector under different carbon targets

## Hydrogen Generation from Bio-waste & Its Application as a Fuel

The biological approaches of $H_2$ manufacture by the achievement of microbes on wastewater and biomass wastes are precisely significant as it consumes waste, aiding the decrease of garbage volume, it can be applied to wastewater, which results in wastewater treatment, and the method is free of greenhouse gas emissions. The biological hydrogen production brings clean hydrogen with an eco-friendly technology and is precisely appropriate for the conversion of wet biomass on a small scale.

The hydrogen is measured as a clean fuel because, on combustion, it generates water. Therefore, principally, Hydrogen is renewable, as it can be transformed from by-products.

- It has a very high energy content per unit mass. Currently, only 40 % of hydrogen is produced from natural gas, 30 % from heavy oils and naphtha, 18 % from coal, and 4 % from electrolysis, and about 1 % is produced from biomass.
- The approaches used today use natural gas as input, thus producing $CO_2$ and other waste gases. The electrolysis of water looks like a clean process, but the electrical power required to drive the electrolysis process comes from thermal or nuclear power plants, which indirectly create pollution. In the coal gasification route, a large amount of waste gases are formed, containing sulphur compounds, thus highly polluting.
- To meet the emission levels of $CO_2$ as imposed by the Kyoto protocol, hydrogen should be formed from renewable energy sources.
- Indirect hydrogen production by electrolysis using electricity from renewable resources, such as sunlight, wind, and hydropower, is also likely to integrate the tag of pollution-free hydrogen generation. The hydrogen is a natural, however transient, by-product of numerous microbial-determined biochemical reactions, mostly in anaerobic fermentation processes.

In addition, certain microorganisms can produce enzymes that can yield $H_2$ from water if an outside energy source, such as sunlight, is available. Various microorganisms are capable of producing hydrogen from monosaccharides and disaccharides, starch, and hemicellulose under anaerobic conditions. Hence, the anaerobic production of hydrogen is common.

### Direct biophotolysis

In a direct biophotolysis, $H_2$ production is a biologically mediated process that uses solar energy and photosynthetic systems of algae to change water into chemical energy (Frock et al., 2010).

$2H_2O$ + solar energy → $2H_2 + O_2$.

The two photosynthetic systems (PS) responsible for the photosynthesis process are as follows:

1. Photosystem I (PS I) produces reductant for $CO_2$.
2. Photosystem II (PS II) splits water to evolve $O_2$.

In the above process, two protons ($H^+$) are released. In the existence of the enzyme “Hydrogenase”, these two protons can yield one molecule of hydrogen ($H_2$). The hydrogenase enzyme is present in green algae and cyanobacteria; thus, they possess the ability to generate hydrogen [43].

$$H_2O \rightarrow \text{PSII} \rightarrow \text{PSI} \rightarrow \text{Fd} \rightarrow \rightarrow \text{Hydrogenase} \rightarrow H_2 \downarrow O_2$$

Since hydrogenase is sensitive to oxygen, it is necessary to maintain the oxygen content at a low level (under 0.1%) so that hydrogen production can continue. This condition can be achieved by the use of green algae, *Chlamydomonas reinhardtii,* which can reduce oxygen during oxidative respiration. Though the reaction is very short-lived and the rate of the hydrogen production is very low, less than one-tenth of that of other photosynthetic reactions [35, 38, 40, 42].

### Indirect Bio-photolysis

In indirect bio-photolysis, the problem of the sensitivity of the $H_2$ evolving process to $O_2$ is typically avoided by separating $O_2$ and $H_2$. In this method, $CO_2$ is intermittently fixed and released, serving as the electron carrier between the $O_2$-producing (water splitting) reaction and the $O_2$-sensitive hydrogenase reactions.

In this model, the algae undergo a cycle of carbon dioxide ($CO_2$) fixation into storage carbohydrates (including starch, glycogen), followed by their transformation into hydrogen $H_2$ by dark anaerobic fermentation processes. In a typical indirect bio-photolysis, hydrogen ($H_2$) is formed as follows: [7].

$$12H_2O + 6CO_2 \rightarrow C_6H_{12}O_6 + 6O_2\ C_6H_{12}O6 + 12H_2O \rightarrow 12H_2 + 6CO_2$$

C) Photo-fermentation $H_2$ production by purple non-sulphur bacteria is mainly due to the presence of the enzyme-nitrogenase under oxygen-deficient conditions, using light energy and reduced compounds (organic acids).

The reaction is as follows: $C_6H_{12}O_6$ + $12H_2O$ + Light energy → $12H_2$ + $6CO_2$.

The general biochemical pathways for the photo-fermentation process can be stated as follows:

$(CH_2O)\ _2 \rightarrow$ (NADPH) Ferredoxin → Nitrogenase (Enzyme) $\uparrow$ ATP $\downarrow H_2$

The numerous types of green algae and cyanobacteria can also fix $CO_2$ via photosynthesis, and consume the capacity to fix

**Comparative Table 2:** Transformative Hydrogen Production Approaches Surpassing MABC Technologies.

| Technology | Principle | Major Advantages Over MABC | Key Limitations | Typical $H_2$ Yield / Efficiency | Transformative Features | Representative References |
|---|---|---|---|---|---|---|
| **Microalgae–Bacterial Consortium (MABC)** | Symbiotic interaction between algae and bacteria for biohydrogen production | Sustainable, wastewater remediation, $CO_2$ sequestration | Low hydrogen yield, oxygen-sensitive hydrogenase, photoinhibition, unstable consortia | Generally low–moderate yields | Integrated bioremediation + hydrogen production | [50, 55] |
| **Hybrid Dark Fermentation–Photofermentation (DF–PF)** | Sequential conversion of substrates via fermentative and photosynthetic bacteria | Higher substrate utilization and hydrogen recovery than MABC | Light dependence and reactor complexity | Up to ~10–12 mol $H_2$/mol glucose theoretically | Nearly complete conversion of VFAs into $H_2$ | [47, 53] |
| **Microbial Electrolysis Cells (MECs)** | Electroactive bacteria produce electrons for cathodic hydrogen evolution | Higher efficiency, continuous production, wastewater treatment integration | Electrode and catalyst costs | $H_2$ recovery efficiencies >80% reported | Bioelectrochemical enhancement of hydrogen generation | [52]; Kadier et al., 2016 |
| **Synthetic Biology/ Engineered Microbes** | Genetic modification of algae, cyanobacteria, or bacteria for enhanced $H_2$ metabolism | Oxygen-tolerant hydrogenases, improved electron transfer, higher productivity | Regulatory and genetic stability concerns | Significantly improved metabolic conversion efficiencies | CRISPR-enabled metabolic engineering | Ghirardi et al., 2009; [57] |
| **Photoelectrochemical (PEC) Water Splitting** | Semiconductor photoelectrodes convert solar energy into hydrogen | Much higher solar-to-hydrogen efficiency than biological systems | High material cost and stability challenges | Solar-to-$H_2$ efficiencies exceeding many biological systems | Artificial photosynthesis platforms | [51, 56] |
| **Thermochemical Gasification** | High-temperature conversion of biomass/waste into syngas and hydrogen | Industrial scalability and rapid production | High energy demand and tar formation | High volumetric hydrogen production | Waste-to-hydrogen industrial platforms | [49] |
| **Plasma-Assisted Hydrogen Production** | Plasma energy dissociates hydrocarbons or water molecules | Rapid conversion and high reaction rates | High electricity requirement | High hydrogen productivity | Low-carbon methane cracking and waste valorization | [54] |
| **Nanomaterial-Assisted Biohydrogen Systems** | Nanoparticles enhance microbial electron transfer and catalysis | Enhanced biofilm conductivity and hydrogenase activity | Nanotoxicity and secondary pollution risks | Improved hydrogen evolution rates | Conductive nanocomposite reactors | Zhang et al., 2022 |
| **Artificial/Synthetic Microbial Consortia** | Rationally designed microbial communities with division of metabolic labor | Better metabolic coordination than natural MABC | Complex community management | Improved stability and productivity | Programmable microbial ecosystems | [48] |
| **AI-Integrated Smart Biohydrogen Systems** | Machine learning optimizes reactor operation and microbial performance | Real-time optimization and predictive control | High computational and sensor requirements | Enhanced process stability and energy efficiency | Autonomous hydrogen biorefineries | [55] |

nitrogen from the atmosphere and yield enzymes that can catalyse the second $H_2$-generating step. The enzyme nitrogenase, which fixes nitrogen, is contained inside the heterocyst; it delivers an $O_2$-free environment to carry out the $H_2$ development reactions [16, 37]. The benefit of this process is in the resourceful metabolic capabilities of these microorganisms and the deficiency of Photosystem II (PSII), which routinely eliminates the problems related to $O_2$ inhibition of $H_2$ production. The major bottlenecks of the technique include low photochemical efficiencies (3-10 %). Moreover, the homogeneity of the light supply in the reactor also contributes to lowering the overall light conversion productivity [5, 15, 39].

## The Biological Hydrogen Production Process

The **Biological Hydrogen Production** process utilizes certain microbes, including specific algae and bacteria, to generate hydrogen through biological means. These organisms harness sunlight or alternative energy sources to split water molecules. Research into biological hydrogen production has demonstrated its potential for providing ecological and renewable hydrogen generation. The potential of biological hydrogen production in renewable energy showcases its capability to catalyze various processes, such as biodiesel and biohydrogen production. Biochar also plays a role in water splitting, the conversion of methane to hydrogen, electricity generation in microbial fuel cells, and hydrogen production via anaerobic digestion. In the context of microbial fuel cells, biochar acts as an electrode, facilitating electron flow through redox (reduction-oxidation) reactions. During these reactions, the oxidation of organic compounds releases electrons, creating a current. Unlike direct combustion of biochar for electricity generation, microbial fuel cells do not rely on heat energy. In microbial fuel cells, electrons flow from the anode to the cathode through an external circuit, completing the reduction process and generating electrical energy. With wider application, microbial fuel cells could potentially produce sufficient electricity for various uses. Their implementation in wastewater

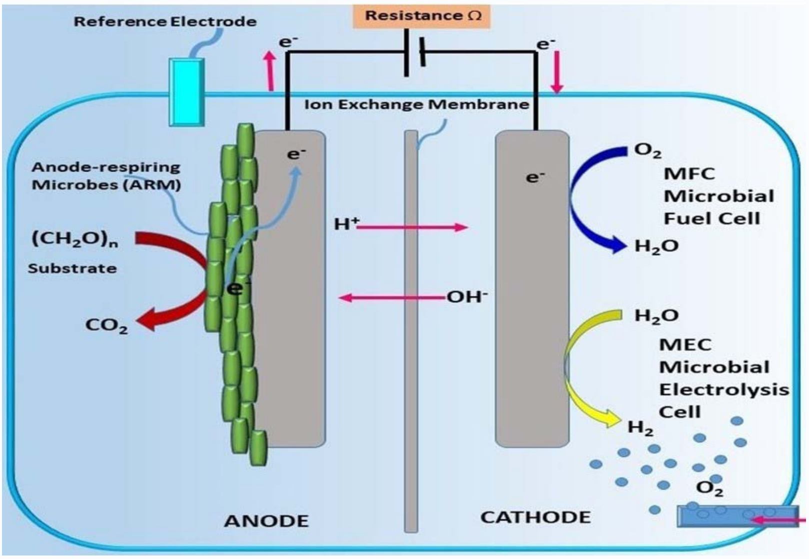

**Figure 2:** Microbially Catalyzed Electrolysis Cells (MECs) [45].

treatment is particularly promising, as these systems can transform sludge—rich in organic compounds, into renewable energy by leveraging the natural decomposition processes of microbes. Notably, the microbes in wastewater not only convert biomass energy into electrical energy but also help reduce sludge production and lower the chemical oxygen demand (COD) of wastewater, which is crucial for improving the efficiency of wastewater treatment processes [29-32]. The global research community firmly acknowledges the transformative potential of microalgae-based hydrogen generation, a fact supported by a rapidly expanding body of literature on the subject.

## In the Photovoltaic-Electrolysis Process

In the Photovoltaic-Electrolysis process, researchers are using photovoltaic cells (solar panels) to directly split water into hydrogen and oxygen. These cells absorb sunlight and convert it into electricity, which drives the electrolysis process without relying on external electricity sources, thereby reducing the carbon footprint. Advancements in the quality of solar panels, catalysts, and system design are essential for improving the efficiency and cost-effectiveness of this method. The low-cost production of hydrogen could enable agriculturalists to become self-sufficient in their energy needs or create new streams of income. Current research is focused on using more affordable catalysts, such as iron, cobalt, and nickel, as substitutes for expensive and rare materials like platinum in the water electrolysis process. These catalysts can enhance reaction kinetics and reduce energy requirements, resulting in a hydrogen production method that is both manageable and environmentally friendly, while utilizing low-cost materials.

## Electrolytic Ozone Generation

Electrolytic ozone generators operate by using an electrical discharge in water to split water molecules ($H_2O$) into hydrogen ($H_2$) and oxygen ($O_2$). This oxygen can then be further split into individual oxygen atoms (O) and recombined to form ozone ($O_3$). To achieve this, a method is needed to isolate the oxygen from hydrogen and to electrically charge the oxygen to create ozone. In this context, nanocatalyst, nanobiochar emerges as an eco-friendly and energy-efficient component for construction materials. Its exceptional ability to reduce thermal conductivity and enhance insulation makes it a valuable addition to the building sector. Incorporating biobased nanocatalysts into construction can lead to more sustainable infrastructure developments. By optimizing a structure's thermal performance with nanocatalyst, nanobiochar, or biochar, there is a significant reduction in energy demands, particularly for temperature regulation. As a result, this not only lowers energy bills substantially but also minimizes the environmental impact of buildings.

## Microbially Catalyzed Electrolysis Cells (MECs)

Microbially Catalyzed Electrolysis Cells (MECs) are poised to revolutionize hydrogen ($H_2$) production by efficiently transforming soluble organic matter in wastewater into an invaluable energy resource. Acetate is the standout carbon source, while volatile fatty acids derived from dark fermentation significantly boost hydrogen yields. MECs are built from four indispensable components: a cathode, an anode, an external electrical connection, and a cation exchange membrane that separates the electrodes (Figure 2).

Bacteria residing on the anode oxidize carbon sources, generating carbon dioxide, electrons, and protons. The electrons are then funneled to the cathode, where they combine with protons to produce hydrogen gas. Operating at a mere 0.11 volts—dramatically lower than the 2.4 volts required for traditional electrolysis—MECs effectively minimize energy loss and electrode resistance. This positions the technology for rapid and widespread adoption. While challenges such as methanogenic electron loss and high membrane costs exist, they are easily surmountable. Furthermore, with the integration of dark fermentation, MECs achieve extraordinary hydrogen production efficiencies of up to 98%, far exceeding conventional methods. The future of sustainable hydrogen production is not just a possibility; it is an imminent reality, with MECs leading the charge toward this new energy frontier [20, 21, 25, 44-46].

## Envisioning a Sustainable Economic Future

The biohydrogen production represents a promising solution for sustainable energy by converting renewable biomass and waste into hydrogen through biological processes such as fermentation and photolysis. This carbon-neutral method provides a viable alternative to hydrogen derived from fossil fuels. The economic feasibility of this approach relies on the use of low-cost feedstock's, including agricultural residues and organic waste, which also contribute to reducing reliance on fossil fuels and mitigating greenhouse gas emissions. Nonetheless, several challenges persist, such as improving hydrogen yields, enhancing process productivity, and transitioning from laboratory-scale research to industrial-scale production. Addressing these challenges can unlock the full potential of biohydrogen as a significant contributor to a cleaner energy future.

### Economic Concept

- Cost-effective Feedstocks: Biohydrogen production harnesses low-cost materials like agricultural waste and food scraps, making it a strong alternative to costly fossil fuels.
- Waste Valorization: This process converts waste biomass into energy, reducing disposal costs while creating a valuable resource.
- Integrated Multi-Generation Systems: Advanced systems produce biohydrogen alongside vital energy outputs such as electricity and hot water, maximizing efficiency and boosting returns.
- Technological Advancement: Focused research aims to enhance efficiency and lower production costs, positioning biohydrogen as a competitive alternative to traditional methods, with investment in development being essential for progress.

### Sustainability Aspects

- Harnessing Renewable Resources: Transforming the landscape of biohydrogen production by leveraging renewable sources such as biomass and microalgae, establishing a formidable alternative to fossil fuel-derived hydrogen.
- Championing Carbon Neutrality:
- The process is inherently carbon-neutral, with carbon dioxide emissions efficiently absorbed by biomass, creating an effective closed-loop system that sets the standard for sustainability.
- Driving Pollution Control and Waste Reduction:
- By harnessing organic waste, we decisively reduce pollution from incineration and landfilling, positioning ourselves as leaders in the quest for a cleaner environment.
- Delivering Environmental Benefits:
- The combustion of biohydrogen produces only pure water vapor, eliminating pollutants like hydrocarbons and carbon monoxide, and showcasing our commitment to ecological integrity.
- Maximizing Yields and Productivity:
- Committed to conquering the challenges of low yields and slow production rates, particularly in dark fermentation, ensuring our processes are as productive as possible.
- Revolutionizing Feedstock Pretreatment:
- Implement advanced pretreatment techniques that will maximize hydrogen yields from complex biomass, driving efficiency to new heights.
- Scaling for Industrial Impact:
- Poised to transition into large-scale applications, confidently tackling the necessary infrastructure challenges that accompany this initiative.
- Optimizing Processes for Superior Efficiency:

Ground-breaking research employs advanced technologies like nanomaterials and artificial intelligence to dramatically enhance hydrogen generation efficiency, leading us into a sustainable energy future.

In response to global warming and pollution, the United Nations has defined the Sustainable Development Goals (SDGs) for 2030. These goals emphasize the urgent need for clean energy, sustainable growth, and innovative technologies to combat climate change [12, 13, 18, 31, 32, 36]. Green industries will experience significant growth, with the International Energy Agency (IEA) declaring that by 2030, renewables will dominate electricity generation. As nations uphold their climate commitments and invest in low-carbon technologies, they will build strong economies that effectively reduce emissions. A sustainable future is not just possible; it is essential.

## Conclusion

Microalgae-based biohydrogen (bio-H2) production presents a promising avenue for sustainable energy. To fully realize its potential, it is vital to tackle key technical and economic challenges that will ensure commercial viability. This includes advancing bioreactor design for scalability and improving biomass harvesting and hydrogen separation techniques to enhance production efficiency. Adopting innovative strategies such as bioelectrochemical systems, genetic modifications of hydrogen-producing organisms, and the optimization of metabolic pathways will be essential for increasing hydrogen yields and reducing costs. Interdisciplinary collaboration among microbiology, biotechnology, and engineering is crucial for developing resilient microalgal strains and effective bioprocesses. Additionally, creating advanced feedstock pretreatment methods will help minimize inhibitors and reduce byproducts during dark fermentation. Finally, by embracing the biorefinery concept, which focuses on producing valuable co-products like bioethanol, bioplastics, and biotherapeutics alongside hydrogen, we can significantly improve the economic feasibility of bio-$H_2$ production and advance toward a sustainable energy future. Microalgal-based wastewater treatment technology represents a potent and sustainable solution that aligns seamlessly with the principles of a circular bioeconomy. By producing oxygen, microalgae eliminate the need for expensive aeration processes, thereby enhancing economic efficiency. Photosynthetic microbial fuel cells (MFCs) provide a transformative approach, integrating bioenergy production, pollutant removal, recovery of valuable byproducts, and effective wastewater treatment. This comprehensive strategy not only addresses critical environmental challenges but also strengthens our commitment to a sustainable future and the goals of a circular bioeconomy.

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