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Exploring the potential of biohydrogen as a sustainable energy solution for Pakistan: A review of production processes and policy challenges

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Abstract

Due to growing carbon dioxide emissions and the depletion of fossil-based energy sources, international studies have been focusing more intensely on developing hydrogen as a source of renewable energy. Biohydrogen is an exciting and green alternative energy source with various different benefits. Unlike traditional energy sources, biohydrogen production does not emit pollutants, making it a more environmentally friendly option. Biohydrogen generation, particularly from microalgae and other low-cost biomass feedstocks, so offers the dual benefit of delivering clean electricity while absorbing Carbon Dioxide. This research investigates the possibility of biohydrogen as a sustainable energy solution for Pakistan's climate issue. We examine the current state of biohydrogen generation technologies, such as dark fermentation, photo fermentation, bio photolysis, with a focus on their potential application in Pakistan. The study investigates global advances in biohydrogen research and their significance in Pakistan, demonstrating biohydrogen's potential contribution to Pakistan's energy independence and environmental targets, as well as the practical and policy-related challenges that must be addressed to advance biohydrogen energy generation and wider adoption.

Keywords: Biohydrogen; Renewable energy; Microalgae; Carbon dioxide reduction; Sustainable energy

1. Introduction

Pakistan, a country of more than 230 million people, is dealing with the twin issues of energy constraint and the growing effects of climate change[1]. The country is very exposed to climate change, with its geographical and socioeconomic circumstances making it among the most climate-sensitive countries in the world. Pakistan is currently facing serious events caused by climate change such as floods, droughts, and heatwaves, which had severe impacts on agriculture, water resources, infrastructure, and public health. These issues are made worse by Pakistan's rising energy demands, which are largely fulfilled through fossil fuels. The dependence on fossil fuels not only adds to global greenhouse gas (GHG) emissions, but it also worsens local air pollution, causing serious risks to health.

Pakistan's dependence on imported energy sources, which account for about a third of its resources, including oil, coal, and LNG, offers long-term difficulties to energy security[2]. The country's reliance on an import-driven energy policy is depleting its foreign exchange reserves and making it vulnerable to international energy price fluctuations, leading to inflationary pressures that could undermine export competitiveness and economic stability. To tackle energy insecurity and ensure long-term sustainability, we recommend transitioning to green energy solutions such as distributed solar power and smart metering, along with enforcing building insulation standards.

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Pakistan has introduced new policies to reduce carbon emissions under its National Action Plan on Climate Change. Studies indicate that the cumulative greenhouse gas emissions from developing countries account for up to 75% of global emissions[3]. The worldwide bioenergy sector will rely largely on biohydrogen as a sustainable and pollution-free fuel for economic development. In these circumstances, experts around the world created a strong interest in the advancement of hydrogen fuel. However, traditional hydrogen generation methods, including Steam methane reforming, autothermal reforming, and partial Oxidation and splitting of water were found to be less economical as it needs considerable costs and energy input; consequently, sustainable affordable approaches for hydrogen production can be achieved from biological means [4] . Anaerobic digestion produces hydrogen as an intermediate product a technical procedure that is now in use for methane generation [5]. Biohydrogen is hydrogen that is produced biologically. The biological processes involved in hydrogen synthesis depend on the existence of an enzyme that produces hydrogen. All known enzymes that can evolve hydrogen are complex, according to a survey of the literature. Metallo-clusters are active locations. Three enzymes now handle this reaction: Ni-Fe-hydrogenase, Fe-hydrogenase, and nitrogenase. Fe-hydrogenase is the enzyme used in bio photolysis, while nitrogenase is used in photo-fermentation processes. Green microalgae, photosynthetic bacteria, dark fermentative bacteria, and cyanobacteria are some of the microorganisms utilized to produce biohydrogen. Researchers' interest in microalgae has grown recently because of its unique properties, which include high growth rate, biomass output, environmental tolerance, and others, that make it a viable source of hydrogen [6].

Various techniques, such as bio-photolysis (both direct and indirect), photo fermentation, dark fermentation, and two-stage methods, are being explored to efficiently harness biohydrogen. These methods offer sustainable alternatives with lower environmental impact. This paper presents an overview of various bioprocesses for hydrogen production, including problems and suggested solutions based on current investigations. Government actions in of policy structures and program activities are examined in order to identify hurdles and make policies and recommendations for developing the biohydrogen economy.

2. Biohydrogen Production Processes

There are two basic types of Biohydrogen production processes while there are also other methods such as microbial electrolysis cell (MECs). These methods are selected due to their relevance and applicability to Pakistan's environmental conditions. MECs and similar advanced technologies, though promising, require specific infrastructural setups, resources, and operational conditions that may not be readily available or feasible in Pakistan's current context. Therefore, this study emphasizes biohydrogen production methods that are not only technologically viable but also align with the local environmental, economic, and resource constraints of the country.

- Bio photolysis
- Fermentation

2.1. Bio Photolysis

In biological systems, the process of bio photolysis transforms water into molecules of hydrogen and oxygen when light is present. Photoautotrophs are microscopic organisms that can conduct bio photolysis and can produce organic matter to support their metabolism in the presence of light.

2.1.1. Direct Bio photolysis

The mechanisms involved in photosynthesis in plants and algae are the same. Through photosynthetic processes, solar energy is directly converted to hydrogen in this mechanism. The use of sunlight, microalgae in this process transform water into hydrogen and oxygen. This process is attractive because it uses solar energy to convert water, a readily available substrate, into hydrogen and oxygen. In this process, water is reduced to hydrogen and oxygen using light that is caught by photo systems I (PSI) and II (PSII). The reduction of water is started by the transfer of electrons from photo systems I (PSI) and II (PSII) to ferredoxin, which results in the production of water and oxygen as by-products. However, this method can only create hydrogen under very particular conditions due to the great sensitivity of Fe-hydrogenase activity to oxygen.

$$2H_2O + \text{light energy} \rightarrow 2H_2 + O_2 \ldots\ldots\ldots \quad \text{(i)}$$

A direct bio photolysis process must function at near one atmosphere of O_2, which is a thousand times larger than the maximum likely to be tolerated. As a result, the O_2 sensitivity of the hydrogenase enzyme process remains critical issue. Hydrogen production rates in the order of 0.07 mmol/hr/liter have been reported in the literature for direct bio photolysis [6].

Direct bio photolysis has the benefit of being easily accessible and having high solar energy efficiency. The hydrogenase enzyme's sensitivity to oxygen, which can prevent the synthesis of hydrogen, and the possibility of unregulated paths for the process are some of the difficulties this process encounters.

Potential in Pakistan

Direct bio-photolysis presents a promising opportunity for Pakistan, leveraging the country's abundant sunlight and water resources to produce clean hydrogen. This process, which uses photosynthetic microorganisms to directly convert solar energy into hydrogen, offers a sustainable and environmentally friendly alternative to fossil fuels. With Pakistan's long coastline and extensive arid regions, where sunlight is plentiful throughout the year, direct bio-photolysis could significantly contribute to the country's energy security. By producing hydrogen through renewable means, Pakistan could reduce its dependence on imported fossil fuels, fostering a more self-reliant and resilient energy sector.

Despite its potential, the widespread adoption of direct bio-photolysis in Pakistan faces several challenges. One of the main hurdles is the oxygen sensitivity of the enzymes involved in the process, which reduces the overall efficiency of hydrogen production. Addressing this issue requires ongoing research into more robust microorganisms and enzyme systems that can perform efficiently in oxygen-rich environments. Additionally, supportive policies and investments in infrastructure are crucial for scaling up this technology. By fostering a research-friendly environment and providing incentives for the adoption of renewable energy technologies, Pakistan could fully harness the potential of direct bio-photolysis, contributing to both energy sustainability and the reduction of greenhouse gas emissions.

2.1.2. Indirect Bio photolysis

Separating the evolution of oxygen from the creation of hydrogen either geographically or temporally can help to mitigate the sensitivity issues with the hydrogen evolving process in indirect bio photolysis. Therefore, indirect bio photolysis involves the division of the evolution reactions of H_2 and O_2 into discrete steps, connected by CO_2 fixation/evolution. The process of producing hydrogen as a stopgap between water oxidation and hydrogen synthesis is known as indirect bio photolysis. The unique characteristic of cyanobacteria is their utilization of solar energy as an energy source and CO_2 from the environment as a carbon source which is shown in Equation (ii). First, the cells take in CO_2 to create components of the cell, which are then used to produce hydrogen in Equation (iii). The general mechanism by which cyanobacteria produce hydrogen is reflected in the following processes:

$$12H_2O + 6CO_2 + \text{light energy} \rightarrow C_6H_{12}O_6 + 6O_2 \ldots\ldots\ldots \quad \text{(ii)}$$
$$C_6H_{12}O_6 + 12H_2O + \text{light energy} \rightarrow 12H_2 + 6CO_2 \ldots\ldots\ldots\ldots \quad \text{(iii)}$$

It's a two-step process where the microbe first undergoes oxygenic photosynthesis, which creates carbohydrates that are then stored in the microorganisms' cells, using sunlight, CO_2, H_2O, and nutrients. To create molecular hydrogen H_2, the stored carbohydrates are fermented in a dark, anaerobic environment in the second stage. By separating the release of oxygen and hydrogen, this procedure reduces the possibility of explosive hydrogen and oxygen combinations posing a safety danger. Because of their higher rates of H_2 generation, Anabaena species and strains have been the focus of a great deal of research [4]. Mutant A. variabilis strains have measured a hydrogen generation rate of 0.355 mmol/h/ literin indirect bio photolysis [7, 8].

Potential in Pakistan

Bio-photolysis offers a highly sustainable method for biohydrogen production, making it particularly suitable for Pakistan, a country blessed with abundant sunlight throughout the year. By utilizing photosynthetic microorganisms like algae, bio-photolysis converts solar energy directly into hydrogen, providing a clean, renewable energy source. A significant advantage of this approach is its potential to integrate with wastewater treatment, where algae cultivation can both absorb nutrients from wastewater and produce hydrogen. This integration presents a dual benefit, not only generating clean energy but also contributing to environmental remediation by reducing water pollution. Such a system would align with Pakistan's growing focus on sustainable development and environmental conservation.

In addition to wastewater integration, bio-photolysis could play a strategic role in coastal regions of Pakistan, where both saline water and sunlight are abundant. Coastal areas provide an ideal setting for large-scale algae cultivation without competing for freshwater resources. Harnessing this technology in such regions could significantly boost renewable energy production while utilizing saline or brackish water, which is otherwise unsuitable for conventional agriculture or industry. This approach would diversify Pakistan's energy portfolio, reduce dependence on fossil fuels, and promote energy security in a sustainable manner. Furthermore, it opens up new avenues for research into optimizing algal strains and improving the efficiency of hydrogen production under varying environmental conditions.

2.2. Fermentation

In the fermentation process, organic resources are transformed into hydrogen gas (H_2) by microorganisms functioning in an anaerobic environment. This process produces biohydrogen. First, a suitable, carbohydrate-rich organic substrate (such as sugars or biomass) is chosen and prepared. Inoculums are produced by cultivating microorganisms that can produce hydrogen, most commonly bacteria or algae. After that, the organic substrate and these inoculums are added to a fermentation reactor. Microorganisms in the reactor use enzymatic processes to break down the substrate, producing hydrogen gas as a byproduct in the process. This conversion process is aided by some enzymes, such as hydrogenase. Temperature, pH, and nutrient levels are among the variables that are tracked and changed throughout fermentation to maximize the amount of hydrogen produced. Different techniques are used to recover and purify hydrogen gas as it builds up. Together with other metabolites like organic acids and biomass, hydrogen gas is usually one of the final products of fermentation. This procedure advances bio-based energy technology by providing a sustainable means of extracting renewable energy from organic waste [9, 10].

2.2.1. Photo fermentation

In photo fermentation, the anaerobic bacteria community uses sunlight to transform the organic substrate into carbon dioxide and biohydrogen. Light drives this fermentation process, converting the organic substrate into hydrogen and carbon dioxide by microbiological conversion. Only in the presence of light does this process occur. Without pyruvate breakdown or respiratory ATP problems, microalgae use light to generate energy-rich organic molecules. Hydrogen is produced when electrons from the organic substrate are extracted by photo catabolism and oxidative carbon metabolism. Because bacteria are weak enough to not be able to split water on their own, photosynthetic bacteria employ light energy and reduced molecules (organic acids) to produce molecular hydrogen, which is catalyzed by nitrogenase [11]. In anaerobic environments, these bacteria may, however, utilize oxygen. Electron donors are simple organic acids like acetic acid. To get these electrons to the nitrogenase, ferredoxin needs energy in the form of ATP. This nitrogenase enzyme can convert a proton into hydrogen gas when there is no nitrogen available by using additional energy in the form of ATP [12]. The following is the entire hydrogen generating reaction:

$$C_6H_{12}O_6 + 6H_2O + \text{light energy} \rightarrow 12H_2 + 6CO_2 \ldots\ldots\ldots\ldots \quad \text{(iiii)}$$

Rates of hydrogen generation of between 145 and 160 mmol/h/ liter have been reported in the literature [11]. While photo conversion efficiency for producing hydrogen has been observed to be close to 100%, practical photosynthesis efficiencies have been observed to be lower under ideal conditions. In these microbes, nitrogenase is primarily in charge of producing hydrogen.

Potential in Pakistan

Given Pakistan's high solar exposure, photo fermentation stands out as a promising option for biohydrogen generation, particularly in regions with abundant sunlight. Photo fermentation utilizes photosynthetic bacteria to convert organic substrates, such as agricultural and industrial waste, into hydrogen under light conditions. In a country like Pakistan, where sunlight is plentiful, this method could be highly effective in harnessing renewable energy. By utilizing organic waste, photo fermentation not only contributes to energy production but also offers a solution for managing waste, turning it into a valuable resource. This approach could be especially beneficial in rural areas, where agricultural residues are abundant, providing a decentralized energy solution that supports local communities.

The combination of photo fermentation with dark fermentation has the potential to significantly enhance hydrogen production efficiency. Dark fermentation involves breaking down organic materials into hydrogen without the need for light, while photo fermentation can further convert the byproducts of dark fermentation into additional hydrogen. This integrated approach could maximize the yield of hydrogen from organic waste, making it an even more viable option for sustainable energy generation in Pakistan. However, to fully capitalize on this potential, the development of cost-effective photobioreactors is essential. Affordable and scalable photobioreactor designs could make this technology more accessible to both rural and urban areas, enabling widespread adoption and contributing to the country's renewable energy goals. Additionally, investing in research and development to optimize these systems would further drive down costs, making photo fermentation a cornerstone of Pakistan's sustainable energy strategy.

2.2.2. Dark Fermentation

The process of producing biohydrogen through the fermentation of microorganisms on carbohydrate-rich substrates without the presence of light or water is known as dark fermentation. The process consists of several stages, namely hydrolysis, acidogenesis, and acetogenesis. The microbes get their energy from the electrons in molecules rich in hydrogen. When too many electrons are produced during a metabolic activity, the protons are converted to hydrogen gas. Hydrogen can be produced by anaerobic bacteria grown in the dark on a substrate high in carbohydrates [13, 14]. The majority of hydrogen produced by microorganisms is produced via anaerobic pyruvate metabolism, which happens when various substrates are catabolized. One of two enzyme systems catalyzes the breakdown of pyruvate [15]:

Pyruvate: Formate lyase (PFL)

$$\text{Pyruvate} + \text{CoA} \rightarrow \text{acetyl} - \text{CoA} + \text{formate} \ldots\ldots\ldots\ldots \quad \text{(v)}$$

Pyruvate: Ferredoxin Oxide reductase (PFOR). [5]

$$\text{Pyruvate} + \text{CoA} + 2\text{Fd}_{\text{ox}} \rightarrow \text{acetyl} - \text{CoA} + \text{CO}_2\ 2\text{Fd}_{\text{red}} \ldots\ldots\ldots\ldots\ldots\ldots \quad \text{(iv)}$$

The most widely utilized substrate in fermentations that produce hydrogen is carbohydrates. Different quantities of hydrogen are produced by glucose depending on the fermentation process and final product. Strict anaerobic bacteria can produce up to 4 moles of hydrogen per mole of glucose, but facultative anaerobes like Escherichia coli can only produce up to 4 moles of hydrogen per mole of glucose. For every mole of glucose, two moles of hydrogen can be produced. A hydrogen production rate of 77 mmol/h/literwas achieved in lab studies [15].

Because of its great energy efficiency, this process is favored; nonetheless, improved electron transfer in microbial fermentation is necessary to get past the kinetic and thermodynamic restrictions.

Potential in Pakistan

Dark fermentation holds significant potential for biohydrogen generation in Pakistan, particularly due to the abundance of organic waste from the country's agriculture and food processing industries. These industries produce large amounts of waste, including crop residues, food scraps, and wastewater, which are often neglected or poorly managed. By utilizing this organic waste as a feedstock for dark fermentation, Pakistan can tap into a low-cost and sustainable resource for hydrogen production. This method not only provides a renewable energy solution but also addresses the environmental issues associated with waste disposal. The conversion of agricultural and industrial waste into clean energy can reduce the reliance on fossil fuels while mitigating the environmental impact of waste accumulation.

One of the key advantages of dark fermentation is its potential to be implemented in remote and rural regions. Facilities for dark fermentation can be constructed in areas close to the source of organic waste, offering localized energy solutions that directly benefit rural communities. By producing hydrogen locally, these regions can access clean energy without the need for extensive infrastructure or grid connections. This decentralized energy generation model can promote economic growth by creating jobs in renewable energy and waste management sectors. Additionally, the implementation of dark fermentation could stimulate investments in rural areas, improving living standards and contributing to the overall development of Pakistan's economy. By leveraging its organic waste resources, Pakistan can make significant strides toward energy sustainability and economic resilience.

3. Conclusion and Recommendations

Hydrogen energy is increasingly recognized as a promising sustainable fuel source, with biohydrogen production offering a particularly attractive pathway due to its potential for low environmental impact. However, in Pakistan, as in many other developing countries, biohydrogen production is still in its infancy and primarily limited to laboratory-scale operations. These operations typically rely on pure substrates like glucose and cellulose. While these substrates are effective for biohydrogen production in controlled environments, they are not economically viable for large-scale or industrial applications due to their high cost.

The high expense associated with pure substrates is a significant barrier to scaling up biohydrogen production. As a result, researchers and industry stakeholders are exploring alternative, more cost-effective substrates. Industrial wastewater, sludge, municipal solid waste, farm waste, and household wastewater have emerged as promising alternatives. These materials not only reduce the cost of biohydrogen production but also offer the added benefit of waste management, turning waste products into valuable resources for energy generation. This approach aligns with the principles of a circular economy, where waste is minimized, and resources are reused, thus enhancing the overall sustainability of the process.

Despite the technical potential of biohydrogen, the transition from lab-scale to industrial-scale production in Pakistan faces several challenges. A key factor is the need for substantial investment in research and development (R&D). To build a biohydrogen-based economy, R&D activities must be adequately supported by the government, both in terms of funding and the creation of an enabling environment for innovation. This includes the development of infrastructure, human resources, and technology transfer mechanisms to facilitate the scaling up of biohydrogen production.

In recent years, the Pakistani government has taken steps to promote renewable energy, including hydrogen energy, through various policies and programs. However, these initiatives have encountered several policy-related challenges that have impeded their effectiveness. For instance, the lack of a cohesive national strategy for hydrogen energy, coupled with regulatory and bureaucratic hurdles, has slowed progress. Additionally, there is often a disconnect between policy formulation and implementation, with insufficient coordination among the relevant government agencies, industry players, and research institutions.

To overcome these challenges, an integrated approach is needed. This would involve combining recent scientific and technological advancements in biohydrogen production with a comprehensive and supportive policy framework. Such a framework should address the entire value chain of biohydrogen production, from feedstock procurement and processing to production, distribution, and end-use applications. It should also include incentives for private sector investment, capacity-building initiatives for researchers and industry professionals, and mechanisms for public-private partnerships.

Furthermore, public awareness and education campaigns are crucial to garnering support for biohydrogen energy and ensuring its acceptance as a mainstream energy source. Stakeholders, including policymakers, industry leaders, and the public, need to be informed about the benefits of biohydrogen and the role it can play in Pakistan's energy transition and economic development.

In conclusion, by leveraging recent scientific discoveries and fostering a conducive policy environment, Pakistan has the potential to develop a thriving biohydrogen economy. This would not only contribute to the country's energy security and sustainability goals but also position Pakistan as a leader in the emerging global bioeconomy.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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