Nativa, Sinop, v. 13, n. 1, p. 46-54, 2025.
Pesquisas Agrárias e Ambientais
DOI: https://doi.org/10.31413/nat.v13i1.18680

ISSN: 2318-7670

Biohydrogen as a renewable energy source: production technologies, feedstock efficiency, and applications in agriculture

Bagus IRAWAN *[1], Syafrudin SYAFRUDIN [2], Mochamad Arief BUDIHARDJO [2]

[1] Doctorate Program in Environmental Science, School of Postgraduate Studies, Universitas Diponegoro, Indonesia.
[2] Department of Environmental Engineering, Faculty of Engineering Universitas Diponegoro, Semarang, Indonesia.
*E-mail: bagusirawan.mt@gmail.com

Submitted: 11/08/2024; Accepted: 01/30/2025; Published: 03/07/2025.

ABSTRACT: This review examines biohydrogen's potential as a renewable energy source, focusing on production technologies, feedstock efficiency, and agricultural applications. Key technologies include dark fermentation, which has been identified as an efficient, environmentally friendly process for biohydrogen production from organic waste and agricultural residues. The study highlights the benefits of biohydrogen for sustainable agriculture, including reduced carbon emissions and energy efficiency. Quantitative data supports biohydrogen's role in decarbonizing agriculture, particularly in energy-intensive activities like irrigation and soil preparation. The findings suggest that biohydrogen can be sustainably integrated into agricultural systems, providing a circular economy solution by converting waste into high-energy, low-emission fuel.
Keywords: sustainability; agricultural energy; biomass conversion; dark fermentation; carbon reduction.

Biohidrogênio como fonte de energia renovável: tecnologias de produção, eficiência de matéria-prima e aplicações na agricultura

RESUMO: Esta revisão examina o potencial do biohidrogênio como fonte de energia renovável, com foco em tecnologias de produção, eficiência de matéria-prima e aplicações agrícolas. As principais tecnologias incluem a fermentação escura, que foi identificada como um processo eficiente e ecologicamente correto para a produção de biohidrogênio a partir de resíduos orgânicos e resíduos agrícolas. O estudo destaca os benefícios do biohidrogênio para a agricultura sustentável, incluindo redução das emissões de carbono e eficiência energética. Os dados quantitativos apoiam o papel do biohidrogênio na descarbonização da agricultura, particularmente em atividades com uso intensivo de energia, como irrigação e preparação do solo. As descobertas sugerem que o biohidrogênio pode ser integrado de forma sustentável aos sistemas agrícolas, fornecendo uma solução de economia circular ao converter resíduos em combustível de alta energia e baixa emissão.
Palavras-chave: sustentabilidade; energia agrícola; conversão de biomassa; fermentação escura; redução de carbono.

1. INTRODUCTION

In recent decades, biohydrogen has attracted widespread attention as a renewable energy source that has the potential to be significant in reducing global carbon emissions and supporting energy sustainability (AKRAM et al., 2024; FAWAD et al., 2024; NAIDOO et al., 2024; THIRUMALAIVASAN et al., 2024). Biohydrogen as renewable energy provides an environmentally friendly alternative to fossil fuels that produce high carbon emissions (YÖRÜKLÜ et al., 2023). One of the main focuses of biohydrogen is its ability to be produced from a variety of biomass sources, including organic waste, which is compatible with circular economy approaches and agricultural waste utilization (GORIA et al., 2024; MUSHARAVATI et al., 2024; RANI et al., 2024).

Biohydrogen can be obtained through a variety of methods, including dark fermentation, which has been identified as one of the most efficient and environmentally friendly production methods for organic waste (MARTÍNEZ-FRAILE et al., 2024; SRIVASTAVA et al., 2024; YÖRÜKLÜ et al., 2023). Biohydrogen produced from dark fermentation allows the conversion of various biomasses into hydrogen gas with much lower emissions than conventional methods such as methane reforming (POMDAENG et al., 2024). In addition, the efficiency of biohydrogen in reducing dependence on fossil fuels is very relevant for developing countries with limited clean energy sources and high dependence on non-renewable energy sources (MACHHIRAKE et al., 2024).

Furthermore, biohydrogen provides other advantages in agriculture, such as supporting agricultural machinery and irrigation systems without causing damaging environmental impacts (KUMAR SHARMA et al., 2022; SINGH et al., 2023). Biohydrogen also allows the use of agricultural waste, such as rice straw, livestock waste, and other biomass residues that are often difficult to process, to become an energy source with high calorific value and low carbon emissions (UMUNNAWUIKE et al., 2024). This study will explore various biohydrogen production technologies, especially dark fermentation, and the effectiveness of agricultural raw materials as an energy source that can support sustainability in the agricultural sector.

Biohydrogen is essential as a transition effort to clean energy and as part of a global decarbonization strategy to achieve net-zero carbon emissions by 2050 (UMUNNAWUIKE et al., 2024). As one of the main methods of biohydrogen production, dark fermentation technology has significant advantages in converting various types of organic waste, such as municipal solid waste (MSW) and food waste, into energy-efficient hydrogen (MUSHARAVATI et al., 2024). Biohydrogen production can also be carried out from lignocellulose biomass, which has excellent potential to provide sustainable hydrogen but still faces obstacles in large-scale production processes due to low yields and high costs (SINGH et al., 2023; ELSHOBARY et al., 2024).

Dark fermentation shows promising results in producing biohydrogen from various organic wastes, mainly because this process requires lower costs than other methods and has a more minimal environmental impact (YÖRÜKLÜ et al., 2023). For example, dark fermentation of food waste with the help of biochar from animal manure shows high efficiency in producing hydrogen (POMDAENG et al., 2024). This shows that biohydrogen plays a role in providing renewable energy and reducing the increasing impact of agricultural and urban waste (QYYUM et al., 2022a).

This research focuses on the potential of biohydrogen produced through dark fermentation technology. Various studies show that dark fermentation technology optimizes biohydrogen production by modifying raw materials and using various additives that improve energy conversion efficiency (AZADVAR; TAVAKOLI, 2024; GALAL et al., 2024). Biohydrogen from dark fermentation is also considered to have great potential as an applicable renewable energy source for various sectors, including the agricultural sector, which requires environmentally friendly energy sources to support productivity without causing adverse environmental impacts (REN et al., 2024; TAGNE et al., 2024).

Studies show that some raw materials, such as agricultural waste and food processing waste, can provide high hydrogen production yields when optimized in the dark fermentation process (MACHHIRAKE et al., 2024). Biohydrogen yield can also be increased by combining dark fermentation technology with artificial intelligence modeling models, which can predict and optimize hydrogen production yields through various approaches (REZK et al., 2024). In addition, data-driven approaches such as technical-economic analysis (TEA) and life cycle analysis (LCA) make a significant contribution to understanding the long-term impact of biohydrogen on the environment and the economy, further reinforcing the urgency of biohydrogen as the energy of the future (EL-QELISH et al., 2024).

This study aims to present a comprehensive analysis related to the potential of biohydrogen as a renewable energy by considering sustainability aspects and its application in the agricultural sector. In this regard, dark fermentation will be studied in depth as the primary method of biohydrogen production, as well as the effectiveness of feedstocks from relevant agricultural wastes to support the sustainability of the agricultural sector (SULTANA et al., 2023; SRIVASTAVA et al., 2024). Further analysis will also include a comparison of the advantages, weaknesses, and challenges in applying biohydrogen, especially in terms of technical and economics for various feedstocks (KIM et al., 2024; LIN et al., 2024).

2. MATERIAL AND METHODS

2.1. Review Methodology

This review process is carried out systematically to identify, collect and analyze the latest scientific literature (from 2018-2024) relevant to biohydrogen production as a renewable energy source. It focuses on three main aspects: production technology, raw material efficiency and its application in the agricultural sector.

- Biohydrogen Production Technology

This review analyses two critical technologies in biohydrogen production, dark fermentation and photobiological, and additional methods such as gasification and microbial electrolysis cell (MEC) systems. The literature examined the mechanisms, advantages, disadvantages, and recent developments of dark fermentation, especially regarding organic waste raw materials and production efficiency. This study also compares the effectiveness of fermentation-based production systems and photobiological approaches, including photobioreactors and algae utilization technology.

- Raw Material Efficiency

This research focuses on the efficiency of agricultural waste-based raw materials such as rice straws, sugarcane bags, and food waste as the main ingredients in biohydrogen production. The analysis results include the potential of each raw material to maximize hydrogen yield, the stability of the production process, and its impact on the environment. Approaches through co-fermentation systems and additives such as iron nanoparticles were also analyzed to improve hydrogen yields and optimize production processes.

- Applications in the Agricultural Sector

The application of biohydrogen in the agricultural sector is mainly reviewed based on its use as an environmentally friendly renewable energy. Biohydrogens are expected to reduce dependence on fossil energy in agricultural operations and provide solutions for managing agricultural and urban waste converted into renewable energy. The relevance of this technology is also evaluated using case studies in various countries with a robust agricultural sector base.

2.2. Selection Criteria

The articles selected in this review focus on the following aspects:

- Production Efficiency

The article studied has indicators of biohydrogen production efficiency, including increased hydrogen yield, the effectiveness of energy conversion from raw materials, and the rate of hydrogen production under optimal conditions.

- Environmental Impact

Focus on studies evaluating carbon emissions, energy consumption, and environmental impacts of biohydrogen production processes, especially using environmentally friendly methods, such as dark fermentation and algae-based photobioreactors.

- Sustainability in the Agricultural Sector

The literacy used also includes articles that discuss the potential for sustainable biohydrogen production in the agricultural sector, emphasizing the use of raw materials from abundant agricultural waste.

3. RESULTS

3.1. Biohydrogen Production Technology

Dark Fermentation

Dark fermentation has become a highly developed method in biohydrogen production, mainly due to its ability to utilize various organic waste substrates. This fermentation involves anaerobic microorganisms that produce hydrogen from organic compounds. Research by Yörüklü et al. (2023) shows that the addition of nanoparticles, such as iron (Fe), nickel (Ni), and magnetite, significantly improves hydrogen yield in laboratory-scale dark fermentation. In addition, adding biochar from elephant manure, according to Pomdaeng et al. (2024), increased microbial activity and hydrogen production efficiency from food waste up to 12.41 mL g^{-1} COD.

Modifying environmental parameters and using biochar as an additive has proven effective in dark fermentation. For example, research by Kovalev et al. (2024) revealed that pretreatment with vortex layer apparatus (VLA) can increase hydrogen yield by up to seven times. In addition, the combination of biochar and nanoparticle concentrations in dark fermentation shows a synergistic effect in increasing hydrogen production, mainly when used with microbial cultures such as *Clostridium* sp. Table 1 confirms the potential of dark fermentation in converting agricultural waste into renewable energy.

Table 1. Raw material efficiency for biohydrogen production through dark fermentation.
Tabela 1. Eficiência da matéria-prima para produção de biohidrogênio por fermentação escura.

Raw Materials	Optimal Conditions	Yield Biohydrogen	Reference
Rice Straw	pH 6.5, temperature 35°C	155 mL H_2/g VS	Machhirake et al. (2024)
Pineapple Waste	pH 6	153.5 mL H_2/g VS	Tagne et al. (2024)
Cassava Waste	pH 5.72	125.67 mL H_2/g VS	Tagne et al. (2024)
Food Waste	Biochar 10 g/L as an additive	12.41 mL H_2/g COD	Pomdaeng et al. (2024)
Sugar Industry Wastewater	pH 7, temperature 37°C	0.649 mol/L H_2	Qyyum et al. (2022a)

Photobiology: Biophotolysis and Photobiology

Biophotolysis techniques that use photosynthetic microorganisms such as algae and cyanobacteria are another promising method in hydrogen production. Singh et al. (2023) found that using photonic energy to break down water molecules in this technique successfully produces hydrogen. However, its efficiency depends on the type of microorganism and the intensity of the light. Direct biophotolysis techniques use sunlight, while indirect biophotolysis methods utilize ultraviolet light, which can improve hydrogen production efficiency through light and substrate optimization.

In addition, photobiological processes on a large scale require adjustment of light intensity and reactor type. Dias et al. (2023) stated that a mathematical model applied to a pilot-scale photobiological reactor showed increased hydrogen production yield of up to 16.03 mmol H2 per hour per cm² when using Tetradesmus obliquus as a culture. Ren et al. (2024) also reported that photobiological fermentation outdoors produces stable hydrogen production efficiency with a 22.8 mL H2/(L·h) production rate. Table 2 compares the effectiveness of methods other than dark fermentation, such as photobioreactors and gasification, which are relevant to biomass sources such as microalgae and other algae biomass.

Table 2. Raw material efficiency for biohydrogen production through photobioreactor and gasification.
Tabela 2. Eficiência de matéria-prima para produção de biohidrogênio por meio de fotobiorreator e gaseificação.

Raw Materials	Optimal Conditions	Yield Biohydrogen	Reference
Microalgae *Chlorella vulgaris*	Low pH, limited sulfur environment	Height (on a laboratory scale)	Singh et al. (2023)
Alga *Tetradesmus obliquus*	Optimal light intensity	16.03 mmol H_2/cm²/jam	Dias et al. (2023)
Bagasse Tebu	Temperature 800°C	14.4% H_2 in syngas	Ajorloo et al. (2024)
Algae Biomass Waste	Gasification temperature 700°C, TiO_2 as catalyst	Up to 62% increase in efficiency	Vinayagam et al. (2024)

Electrolysis and Gasification

The process of electrolysis of biomass has also been widely studied as an alternative to biohydrogen production. Umer et al. (2024) highlighted using polyoxometalate in electrolysis to improve hydrogen production efficiency, especially from biomass with high organic compound content. Edou; Onwudili (2022) emphasizes the use of fluidized bed (FB) gasification combined with carbon capture technology (CCS), which has proven to be effective in producing hydrogen with better quality.

Using agricultural waste, such as wheat straw or coffee grounds, as raw materials in the gasification process produces optimal hydrogen production. For example, Ajorloo et al. (2024) observed that at a gasification temperature of 800°C, the H_2 component in syngas reached 14.4% for wheat straw, which is higher than other substrates. TiO_2-based catalysts, as outlined by Vinayagam et al. (2024), have been shown to increase hydrogen selectivity by up to 18.5%, demonstrating the potential use of this technique in algae-based biomass conversion.

Integration of Dark Fermentation and Photo-Fermentation

Integrating dark fermentation and photo-fermentation shows high hydrogen production efficiency, mainly because substrates are not fully oxidized in dark fermentation. According to Goren et al. (2024), this hybrid process can produce hydrogen of 680.8 mL g^{-1} of biomass, which is higher than conventional methods. Silva et al. (2024) also elaborated that using microbial electrolysis cells (MECs) in combination with photo-fermentation fermentation can improve hydrogen efficiency, especially from industrial wastewater.

Use of Catalysts and Hybrid Systems

The use of catalysts has been shown to affect biohydrogen production through various methods significantly. Elshobary et al. (2024) showed that Mg-Zn ferrite nanoparticles added in fermentation increase enzymatic activity and maximize biohydrogen production from algae substrates. In addition, Ramzan et al. (2023) identified that quantum dots (QD)-based photocatalysts can break β-O-4 bonds on lignin, which aids in hydrogen production.

Hybrid approaches, such as the combination of ANFIS and RTH, have also shown positive results in simulating hydrogen production from microalgae. Rezk et al. (2024) revealed that this algorithm could optimize three main parameters (sulfur concentration, process time, and wet biomass concentration) and provide more accurate predictions of hydrogen results than statistical methods such as ANOVA, with a decrease in RMSE of up to 93.4%.

Artificial Intelligence-Based Approach

Artificial intelligence (AI) technology in biohydrogen production is growing. According to Sultana et al. (2023), the Bayesian (BA) algorithm combined with Support Vector Regression (SVR) can model hydrogen production from food waste with higher accuracy than conventional methods such as response surface methodology (RSM). Azadvar; Tavakoli (2024) also added that the use of machine learning algorithms, such as Gradient Boosting Regressor (GBR) and Ensembled Learning Adaboost Regressor (ELA), has been proven to improve the prediction of hydrogen production efficiency in the supercritical water gasification (SCWG) process of biomass.

The AI-based approach increases biohydrogen production yields through automated optimization of process parameters, especially in complex conditions, such as using lignocellulosic and algae substrates.

Relevance for Agriculture and the Environment

Biohydrogen production from agricultural biomass, such as pineapple and cassava, provides significant results by optimizing pH conditions and process times. Tagne et al. (2024) reported that hydrogen production levels reached 153.5 mL H_2/gVS for pineapple and 125.67 mL H_2/gVS for cassava, with optimal yields at pH 6 and 5.72, respectively. This technique is relevant in the context of using agricultural waste, which has the potential to be a renewable energy source, and it provides solutions for reducing organic waste on agricultural land.

Ultimately, the significant biohydrogen production results from these various methods and feedstocks open opportunities for broader application, especially in the renewable energy and sustainable agriculture sectors.

3.2. Raw Material Efficiency

In this section, an in-depth analysis was carried out related to the use of agricultural waste as raw materials in biohydrogen production, as well as a comparison of the efficiency of various types of raw materials in optimizing and optimizing hydrogen production.

Utilization of Agricultural Waste

Agricultural waste is effective as a feedstock in biohydrogen production, primarily through anaerobic fermentation and dark fermentation methods. According to research by Machhirake et al. (2024), the use of rice straw as a substrate with the addition of activated sludge as an inoculum shows significant results with biohydrogen production efficiency reaching 155 mL g^{-1} VS at pH 6.5 and a temperature of 35°C. The use of a combination of agricultural waste with an anaerobic fermentation process increases the efficiency of hydrogen production by up to 23% compared to no combination of this technology, according to Tagne et al. (2024) that local waste such as pineapple and cassava have great potential in biohydrogen production. Optimization of production conditions at a specific pH increases hydrogen yield from pineapple waste by up to 153.5 mL H_2/gVS and from cassava by 125.67 mL H_2/gVS. The use of this local waste source not only supports hydrogen production but also helps manage organic waste.

Comparative analysis of various types of raw materials shows that the characteristics of the raw materials used most significantly influence the efficiency of hydrogen production. For example, in a study by Fawad et al. (2024), operating parameters such as temperature and pressure affect the hydrogen production yield in sugarcane bagasse raw materials. Increasing temperatures tend to increase hydrogen production, while higher pressures decrease yields. In these simulations, variations in operational parameters can affect the composition of the resulting syngas and the efficiency of the gasification process, demonstrating the importance of optimizing operating parameters for the best results.

In addition, the use of nanoparticles has a positive impact on hydrogen production. Yörüklü et al. (2023) showed that the use of iron nanoparticles in the dark fermentation process increased hydrogen production by up to 31% compared to no additives, while research by Rozina et al. (2024) reported an increase in biohydrogen production by up to 34% with the addition of iron nanoparticles along with the microbial *Clostridium butyricum*.

Overall, using feedstocks in biohydrogen production shows promising results, with an efficiency that can be improved by optimizing process parameters and adding special additives. A comparison of the efficiency of various raw materials also shows that factors such as the type of substrate, environmental conditions, and additives play an essential role in optimizing biohydrogen production.

The following is a Table 3 comparison of the efficiency of various raw materials in biohydrogen production that highlights the hydrogen production potential of various raw materials, the optimal conditions required, and the conversion efficiency in various scenarios.

This table compares raw materials based on hydrogen production efficiency and their respective characteristics. Optimizing conditions like pH and temperature is essential to improving yields. Dark fermentation is efficient for various substrates, whereas biophotolysis gives good results on raw materials such as microalgae. This table shows that agricultural waste has significant potential in supporting sustainable biohydrogen.

Table 3. Process and efficiency of hydrogen production.
Processo e eficiência da produção de hidrogênio.

Raw Materials	Optimal Conditions	Hydrogen Production (mL g^{-1} VS)	Source
Pineapple Waste	pH 6, temperature 35°C	153,5	Tagne et al. (2024)
Cassava Waste	pH 5.72, temperature 35°C	125,67	Tagne et al. (2024)
Banana Peel	pH 5.5, temperature 37°C	49.2 in 1 hour	Umer et al. (2024)
Bagas Sugarcane	1:1 vapor-to-biomass ratio	14.4% of syngas	Fawad et al. (2024)
Glucose	Dark fermentation with Fe^{2+}	192.4 mL g^{-1}	Arun et al. (2022)
Alga (*Chlorella vulgaris*)	Limited nitrogen, biophotolysis	43.2 mL L^{-1}	Singh et al. (2023)
Rice Straw	pH 6.5, temperature 35°C	155	Machhirake et al. (2024)
Sludge	Dark fermentation with *Clostridium butyricum*	5,857 mL L^{-1}	Goveas et al. (2024)

3.3. Applications of Biohydrogen in the Agricultural Sector

Os Renewable Energy for Agricultural Machinery

The potential of biohydrogen as a renewable energy source in agricultural machinery and equipment has been widely analyzed as a step to reduce dependence on fossil fuels. In a recent study, Fawad et al. (2024) found that using biomass waste such as sugarcane bagasse produces hydrogen-rich syngas with reasonably high efficiency through gasification technology. This shows that biohydrogen can replace conventional fuels in tractor engines and tillage equipment.

A study from Singh et al. (2023) revealed that microalgae, specifically *Chlamydomonas reinhardtii* and *Chlorella vulgaris*, are capable of producing significant biohydrogen through the biophotolysis process, a technology that is feasible to apply on a commercial scale. In agricultural environments, this biohydrogen can be used as fuel for equipment with low energy requirements, such as irrigation systems or environmental control equipment in greenhouses.

Sustainability Impact: Lowering the Carbon Footprint in the Agriculture Sector

Biohydrogens are essential in improving the agricultural sector's sustainability through reducing carbon emissions. For example, a study by Machhirake et al. (2024) shows that biohydrogen from agricultural waste, such as rice straw and corn stalks, has the potential to be reused as a source of clean energy in farmland. It can reduce the carbon footprint of the agricultural sector by eliminating the direct burning of biomass that produces large amounts of carbon dioxide (CO_2).

In addition, research from Umunnawuike et al. (2024) reported that dark fermentation of urban and agricultural waste produces biohydrogen with a lower environmental impact. When combined with other processes, such as waste pretreatment, this dark fermentation shows excellent potential in supporting sustainability and energy efficiency in the agricultural sector. Umunnawuike et al. (2024) emphasized that this process reduces greenhouse gas emissions from decaying organic waste in open land.

Using biohydrogen in the agricultural sector as a renewable energy source and reducing the carbon footprint promises significant economic and environmental benefits. Using biohydrogen through effective technology and the abundant management of biomass raw materials, especially agricultural waste, marks a step towards a sustainable agricultural sector.

4. DISCUSSION

4.1. Comparison of Technology and Efficiency of Raw Materials

Biohydrogens in various agricultural applications require an efficient approach to biomass conversion, especially dark fermentation technology, which shows excellence in energy efficiency and utilization of organic waste. According to research by Goveas et al. (2024), dark fermentation technology can produce 5,857 mL/L of hydrogen from a sludge substrate, with advantages in reducing carbon emissions, but faces the challenge of process sensitivity to oxygen. In addition, research shows that this method allows for increased efficiency with the addition of biochar, as shown by Pomdaeng et al. (2024), which stabilizes the fermentation process and increases the hydrogen yield from food waste with the addition of biochar that increases microbial activity.

The availability of raw materials is a decisive factor in choosing biohydrogen technology. In the context of agriculture, sugarcane bagasse, as a by-product of sugarcane plantations, is a raw material that is available in large quantities in many agrarian areas, including Indonesia and Brazil. Fawad et al. (2024) indicated that this waste could produce hydrogen-rich syngas through the gasification process, which shows that gasification technology can match the results of dark fermentation if the available raw materials have high cellulose and lignin content. Overall, the biohydrogen yield from agricultural waste such as sugarcane is greater than that of other food wastes (MACHHIRAKE et al., 2024).

In addition, microalgae such as Chlorella vulgaris also have high potential as feedstocks with efficient hydrogen productivity at laboratory scale and in photobioreactors. Singh et al. (2023) reported that these algae produce higher biohydrogen under sulfur scarcity conditions but need additional large-scale optimization to maintain energy efficiency. The same study found that algae can grow on limited land, making them more suitable for closed systems in controlled environments, such as biorefinery facilities.

On the other hand, Qyyum et al. (2022a) highlighted wastewater from the sugar industry as a potential raw material with high conversion efficiency in dark fermentation, producing more hydrogen than other beverage industry wastes. Using this wastewater in the agricultural sector also shows relevance as it can reduce the cost of raw materials and benefit sustainable industrial waste management. On the other hand, this waste's commercial-scale dark fermentation still has constraints on process stability, especially in maintaining pH and temperature at optimal conditions.

Optimizing hydrogen production efficiency also requires consideration of additives such as nanoparticles, as reported by (YÖRÜKLÜ et al., 2023). The addition of iron nanoparticles has been shown to increase biohydrogen yield up to 3.55 mol H_2/mol of substrate from glucose and increase the effectiveness of dark fermentation in producing hydrogen. Nonetheless, the additional production costs required for these nanoparticles pose a challenge in commercial applications in the agricultural sector, where costs must be kept down to remain economical. Another exciting alternative is the addition of $CaCO_3$ and Tween 20 surfactant reported by El-Qelish et al. (2024), which can increase carbon conversion efficiency by up to 8.7%, making organic raw materials such as used cooking oil (WFO) more competitive. Table 4 strengthens the argument regarding the importance of developing technology to improve the efficiency of biohydrogen in the agricultural sector.

The results of this study underscore the importance of selecting technologies based on locally available raw materials and adjustments to the specific conditions required in the biohydrogen conversion process. In the agricultural sector, the choice of technology and raw materials must consider the availability of organic waste and operational costs, where dark fermentation can be the primary option in the long run if process stability can be overcome.

Table 4. Improvement of biohydrogen yields through additives and optimization of dark fermentation technology.
Tabela 4. Melhoria do rendimento de biohidrogênio por meio de aditivos e otimização da tecnologia de fermentação escura.

Additives/ Supporting Ingredients	Main Raw Materials	Efficiency Increase (%)	Reference
Biochar from elephant manure	Food Waste	21.79%. High efficiency, microbial stability	(Pomdaeng et al., 2024)
Iron (Fe) Nanoparticles	Glucose	31%. 3.55 mol H_2/mol substrate	(Civelek Yörüklü et al., 2023)
Pretreatment Microwave	Industrial Wastewater	High conversion efficiency. Reduces inhibitors	(Onwuemezie & Gohari Darabkhani, 2024)
TiO_2 (0.2 vol%)	Microalgae	H_2 selectivity increased by 18.5%. 23 mol kg^{-1} at 700°C gasification temperature	(Vinayagam et al., 2024)
Tween 20 and $CaCO_3$	Used Cooking Oil (WFO)	Carbon conversion is 8.7% higher. Better conversion efficiency	(El-Qelish et al., 2024)
Biochar from elephant manure	Food Waste	21.79%. High efficiency, microbial stability	(Pomdaeng et al., 2024)

4.2. Challenges and Opportunities in Large-Scale Biohydrogen Production and Contribution to Climate Change

Biohydrogen production is recognized as having great potential as a renewable energy source for climate change mitigation. However, development on an industrial scale faces significant challenges in economic and operational aspects. First, the main challenges are the high investment costs and the need for pretreatment of raw materials to remove inhibitor components, such as in treating industrial wastewater containing sulfide and ammonia compounds (SILVA et al., 2024). Cost optimization and pretreatment techniques are essential for efficient and stable production. Onwuemezie; Darabkhani (2024) also suggest that integration technologies, such as microwave pretreatment, can improve biohydrogen efficiency through increased enzyme activity.

The use of nanoparticles to improve biohydrogen yields is a promising innovation, but the high cost of nanoparticle production is a significant obstacle for large-scale applications (SINGH et al., 2023; YÖRÜKLÜ et al., 2023). Although methods such as TOPSIS are used to determine the most efficient nanoparticles, the cost challenge remains a bottleneck (YÖRÜKLÜ et al., 2023). Similarly, using nanomaterials such as TiO_2 and Fe_2O_3 shows high conversion efficiency, but their synthesis requires large amounts of energy, which complicates commercial application (SINGH et al., 2023).

In addition to technical and economic challenges, large-scale production environments involving microorganisms require careful regulation of substrate and biochar concentrations not to degrade the efficiency of microorganisms (POMDAENG et al., 2024). Research by Machhirake et al. (2024) shows that the stability of the fermentation environment is essential, especially in the use of agricultural and urban waste that requires optimal pH control. In addition, Machhirake et al. (2024) identified that high initial investment is a challenge in industrial-scale development in developing countries. Therefore, policy support for subsidies or investment incentives is crucial in accelerating biohydrogen implementation in developing countries.

In the context of climate change, biohydrogen offers an excellent opportunity to reduce greenhouse gas emissions. Using biohydrogen as a substitute for fossil fuels in the agricultural sector, such as to power agricultural machinery, will help reduce CO_2 emissions and improve the agricultural sector's sustainability (MUSHARAVATI et al., 2024). Integrating biohydrogen technology with other renewable energy sources, such as photovoltaic energy, is also recommended to minimize the environmental impact of biohydrogen production (MUSHARAVATI et al., 2024).

The scalability of biohydrogen production is also a challenge in mitigating climate change. Research by Goren et al. (2024) shows that optimizing the fermentation process with plant substrates can produce more significant and sustainable biohydrogen. However, challenges in biohydrogen storage and system stability during the fermentation process still require further innovation, such as integrating biohydrogen with a biorefinery system that allows for multi-product processing (ZAIDI et al., 2024).

4.3. Research Gap

Biohydrogen production through dark fermentation has challenges in optimizing the efficiency and cost of raw materials. This challenge is especially evident in the sustainability of raw materials and processing technologies, where further research is still needed to develop new sources of raw materials that are more efficient and economical. For example, the use of industrial waste raw materials such as brewery waste has a hydrogen production potential of 3061 mL with a maximum production rate of 129.3 mL/h using a prediction model based on dark fermentation (Qyyum et al., 2022a; Qyyum, Ismail, et al., 2022b). However, sustainable efficiency on an industrial scale is often hampered by high initial investment costs and operational costs, especially in preparing raw materials that require complex pretreatment (MUSHARAVATI et al., 2024).

Further research is also needed to maximize biohydrogen production from other, more affordable sources of organic waste. For example, studies show that applying biochar from elephant manure at an optimal concentration of 10 g/L increases hydrogen production by up to 21.79% (POMDAENG et al., 2024). However, biochar inhibits microorganisms' growth at higher concentrations due to its competitive effects on essential nutrients required for fermentation (POMDAENG et al., 2024). In-depth research on the effects of biochar concentrations or other additives on hydrogen-producing microorganisms is needed so that the development of raw materials can run more optimally without sacrificing production efficiency.

In addition, innovations in fermentation techniques also have great potential in increasing biohydrogen efficiency. For example, using nanomaterials such as TiO_2 and Fe_2O_3 effectively increases hydrogen production yields. However, the high cost of nanomaterial production and the energy requirements for synthesis are significant challenges (SINGH et al., 2023). In a more specific application, Yörüklü et al. (2023) proposed the TOPSIS method to identify nanoparticles with the best efficiency and cost, showing iron nanoparticles as the optimal choice in increasing hydrogen production.

Hybrid methods also have the potential for optimization. Combining dark fermentation with photobiological processes increases hydrogen yield by 23% compared to single fermentation (MACHHIRAKE et al., 2024). However, this technique requires strict temperature and pH management, which is costly, so there is still a need to find more energy-efficient methods to improve the stability of the fermentation environment. Research on the optimal conditions for integrating dark fermentation with photobiological technology needs to be continuously improved to support production efficiency on a large scale (UMUNNAWUIKE et al., 2024).

Developing new strategies in fermentation techniques and biohydrogen feedstocks will significantly contribute to achieving sustainability and efficiency in hydrogen energy production. Facing these challenges requires a multidisciplinary approach involving integrating advanced technologies, such as AI and data-driven process optimization, to maximize the potential of new feedstocks and more economical and environmentally friendly fermentation methods.

5. CONCLUSIONS

Based on the analysis of the existing literature, dark fermentation has proven to be the most effective and sustainable method for producing biohydrogen in the agricultural sector. This method shows high potential for processing agricultural waste as raw materials, converting it into renewable and clean energy with minimal environmental impact. Dark fermentation reduces dependence on fossil fuels and offers a solution for efficiently managing agricultural waste.

Further research is needed to improve the specific utilization of various local raw materials, such as rice straw and livestock manure, which have great potential to increase hydrogen production in the agricultural sector. Optimization of additives such as biochar and affordable nanoparticles is also needed to increase the efficiency and effectiveness of dark fermentation. In addition, it is necessary to develop an adaptive biohydrogen distribution system for applications in the agricultural sector, such as irrigation machines and tractors, which is expected to reduce carbon emissions significantly.

This conclusion supports the initial goal of examining biohydrogen's potential as a renewable energy solution in the agricultural sector. With a proven, efficient and sustainable dark fermentation method, biohydrogen provides an environmentally friendly energy solution and helps create a circular economy using agricultural waste.

6. REFERENCES

AJORLOO, M.; GHODRAT, M.; SCOTT, J.; STREZOV, V. Experimental analysis of the effects of feedstock composition on the plastic and biomass co-gasification process. **Renewable Energy**, v. 231, e120960, 2024. https://doi.org/10.1016/j.renene.2024.120960

AKRAM, F.; FATIMA, T.; IBRAR, R.; UL HAQ, I. Biohydrogen: Production, promising progressions, and challenges of a green carbon-free energy. **Sustainable Energy Technologies and Assessments**, v. 69, e103893, 2024. https://doi.org/10.1016/j.seta.2024.103893

ARUN, J.; SASIPRABA, T.; GOPINATH, K. P.; PRIYADHARSINI, P.; NACHIAPPAN, S.; NIRMALA, N.; DAWN, S. S.; THUY LAN CHI, N.; PUGAZHENDHI, A. Influence of biomass and nanoadditives in dark fermentation for enriched bio-hydrogen production: A detailed mechanistic review on pathway and commercialization challenges. **Fuel**, v. 327, e124112, 2022. https://doi.org/10.1016/j.fuel.2022.125112

AZADVAR, S.; TAVAKOLI, O. Data-driven interpretation, comparison, and optimization of hydrogen production from supercritical water gasification of biomass and polymer waste: Applying ensemble and differential evolution in machine learning algorithms. International **Journal of Hydrogen Energy**, v. 85, p. 511-525, 2024. https://doi.org/10.1016/j.ijhydene.2024.08.081

DIAS, F. G.; VARGAS, J. V. C.; MARTINS, L. S.; ROSA, M. P.; BALMANT, W.; MARIANO, A. B.; PARISE, J. A. R.; ORDONEZ, J. C.; KAVA, V. M. Modeling, simulation, and optimization of hydrogen production from microalgae in compact photobioreactors. **Algal Research**, v. 71, e103065, 2023. https://doi.org/10.1016/j.algal.2023.103065.

EDOU, D. J. N.; ONWUDILI, J. A. Comparative techno-economic modeling of large-scale thermochemical biohydrogen production technologies to fuel public buses: A case study of West Midlands region of England. **Renewable Energy**, v. 189, p. 704-716, 2022. https://doi.org/10.1016/j.renene.2022.02.074

EL-QELISH, M.; EL-SHAFAI, S. A.; AZOUZ, R. A. M.; RASHAD, E.; ELGARAHY, A. M. From seashells to sustainable energy: Trailblazing the utilization of *Anadara uropigimelana* shells for sustainable biohydrogen production from leftover cooking oil. **Journal of Environmental Chemical Engineering**, v. 12, n. 2, e111914, 2024. https://doi.org/10.1016/j.jece.2024.111914

ELSHOBARY, M.; ABDULLAH, E.; ABDEL-BASSET, R.; METWALLY, M.; EL-SHEEKH, M. Maximising biofuel production from algal biomass: A study on biohydrogen and bioethanol production using Mg-Zn ferrite nanoparticles. **Algal Research**, v. 81, e103595, 2024. https://doi.org/10.1016/j.algal.2024.103595

FAWAD, A.; QYYUM, M. A.; UL JABBAR, A. A comprehensive simulation study of integrated gasification, enrichment, and separation processes for biohydrogen production from sugarcane bagasse. **International Journal of Hydrogen Energy**, In Press, 2024. https://doi.org/10.1016/j.ijhydene.2024.05.332

GALAL, A.; ELGARAHY, A. M.; HAROUN, B.; SAFWAT, S. M.; EL-QELISH, M.; FAHMI, A. A. Enhanced biohydrogen production from thermally hydrolyzed pulp and paper sludge via Al2O3 and Fe3O4 nanoparticles. **Chemical Engineering Research and Design**, v. 210, p. 82-96, 2024. https://doi.org/10.1016/j.cherd.2024.08.019

GOREN, A. Y.; DINCER, I.; KHALVATI, A. Green biohydrogen production from renewable plant-based resources: A comparative evaluation. **Process Safety and Environmental Protection**, v. 185, p. 947-977, 2024. https://doi.org/10.1016/j.psep.2024.03.056

GORIA, K.; SINGH, H. M.; SINGH, A.; KOTHARI, R.; TYAGI, V. V. Insights into biohydrogen production from algal biomass: Challenges, recent advancements and future directions. **International Journal of Hydrogen Energy**, v. 52, p. 127-151, 2024. https://doi.org/10.1016/j.ijhydene.2023.03.174

GOVEAS, L. C.; NAYAK, S.; KUMAR, P. S.; VINAYAGAM, R.; SELVARAJ, R.; RANGASAMY, G. Recent advances in fermentative biohydrogen production. **International Journal of Hydrogen Energy**, v. 54, p. 200-217, 2024. https://doi.org/10.1016/j.ijhydene.2023.04.208

KIM, S. M.; SIM, Y. B.; YANG, J.; KO, J.; KIM, D. H.; KIM, S. H. High-rate continuous biohydrogen (Bio-H_2) production from rice straw hydrolysate using a dynamic membrane bioreactor (DMBR). **International Journal of Hydrogen Energy**, v. 71, p. 465-472, 2024. https://doi.org/10.1016/j.ijhydene.2024.05.197

KOVALEV, A. A.; KOVALEV, D. A.; PANCHENKO, V. A.; ZHURAVLEVA, E. A.; LAIKOVA, A. A.; SHEKHURDINA, S. V.; IVANENKO, A. A.; LITTY, Y. V. Energy efficiency of hydrogen production during dark fermentation. **International Journal of Hydrogen Energy**, v. 87, p. 171-178, 2024. https://doi.org/10.1016/j.ijhydene.2024.08.473

LIN, H.; ZHANG, M.; CHAUHAN, B. S.; AYED, H.; KHADIMALLAH, M. A.; TANG, X.; MAHARIQ, I. Development, kinetic analysis, and economic feasibility of different corn stover-driven biorefineries to produce biohydrogen, bioethanol, and biomethane: A comparative analysis. **Renewable Energy**, v. 237, e121625, 2024. https://doi.org/10.1016/j.renene.2024.121625

MACHHIRAKE, N. P.; VANAPALLI, K. R.; KUMAR, S.; MOHANTY, B. Biohydrogen from waste feedstocks: An energy opportunity for decarbonization in developing countries. **Environmental Research**, v. 252, e119028, 2024. https://doi.org/10.1016/j.envres.2024.119028

MARTÍNEZ-FRAILE, C.; MUÑOZ, R.; SIMORTE, M. T.; SANZ, I.; GARCÍA-DEPRAECT, O. Biohydrogen production by lactate-driven dark fermentation of real organic wastes derived from solid waste treatment plants. **Bioresource Technology**, v. 403, e130846, 2024. https://doi.org/10.1016/j.biortech.2024.130846

MUSHARAVATI, F.; AHMAD, A.; JAVED, M. H.; SAJID, K.; NIZAMI, A. S. Advancing biohydrogen production from organic fraction of municipal solid waste through thermal liquefaction. **International Journal of Hydrogen Energy**, In Press, 2024. https://doi.org/10.1016/j.ijhydene.2024.05.144

NAIDOO, J. C.; MOODLEY, P.; SANUSI, I. A.; SEWSYNKER-SUKAI, Y.; MEYER, E. L.; GUEGUIM KANA, E. Microwave-assisted sequential green liquor-inorganic salt pretreatment for enhanced sugar recovery from sorghum leaves towards bioethanol and biohydrogen production. **Renewable Energy**, v. 225, e120225, 2024. https://doi.org/10.1016/j.renene.2024.120225

ONWUEMEZIE, L.; DARABKHANI, H. G. Biohydrogen production from solar and wind assisted AF-MEC coupled with MFC, PEM electrolysis of H_2O and H_2 fuel cell for small-scale applications. **Renewable Energy**, v. 224, e120160, 2024. https://doi.org/10.1016/j.renene.2024.120160.

POMDAENG, P.; CHU, C. Y.; MASA-AD, A.; NGAMNURAK, P.; SETTHAPUN, W.; SINTUYA, H. An innovative acid-resistant elephant dung biochar powder for fermentative biohydrogen production improvement from food waste slurry. **International Journal of Hydrogen Energy**, In Press, 2024. https://doi.org/10.1016/j.ijhydene.2024.10.123

QYYUM, M. A.; IHSANULLAH, I.; AHMAD, R.; ISMAIL, S.; KHAN, A.; NIZAMI, A. S.; TAWFIK, A. Biohydrogen production from real industrial wastewater: Potential bioreactors, challenges in commercialization and future directions. **International Journal of Hydrogen Energy**, v. 47, n. 88, p. 37154-37170, 2022. https://doi.org/10.1016/j.ijhydene.2022.01.195

QYYUM, M. A.; ISMAIL, S.; NI, S. Q.; IHSANULLAH, I.; AHMAD, R.; KHAN, A.; TAWFIK, A.; NIZAMI, A. S.; LEE, M. Harvesting biohydrogen from industrial wastewater: Production potential, pilot-scale bioreactors, commercialization status, techno-economics, and policy analysis. **Journal of Cleaner Production**, v. 340, e130809, 2022. https://doi.org/10.1016/j.jclepro.2022.130809

RAMZAN, H.; USMAN, M.; NADEEM, F.; SHAHZAIB, M.; UR RAHMAN, M.; SINGHANIA, R. R.; JABEEN, F.; PATEL, A. K.; QING, C.; LIU, S.; PIECHOTA, G.; TAHIR, N. Depolymerisation of lignin: Recent progress towards value-added chemicals and biohydrogen production. **Bioresource Technology**, v. 386, e129492, 2023. https://doi.org/10.1016/j.biortech.2023.129492

RANI, P.; KUMAR YADAV, D.; YADAV, A.; RAM BISHNOI, N.; KUMAR, V.; RAM, C.; PUGAZHENDHI, A.; KUMAR, S. S. Frontier in dark fermentative biohydrogen production from lignocellulosic biomass: Challenges and future prospects. **Fuel**, v. 366, e131187, 2024. https://doi.org/10.1016/j.fuel.2024.131187

REN, C.; ZHANG, S.; LI, Q.; JIANG, Q.; LI, Y.; GAO, Z.; CAO, W.; GUO, L. Pilot composite tubular bioreactor for outdoor photo-fermentation hydrogen production: From batch to continuous operation. **Bioresource Technology**, v. 401, e130705, 2024. https://doi.org/10.1016/j.biortech.2024.130705

REZK, H.; ALAHMER, A.; OLABI, A. G.; SAYED, E. T. Application of artificial intelligence and red-tailed hawk optimization for boosting biohydrogen production from microalgae. **International Journal of Thermofluids**, v. 24, e100876, 2024. https://doi.org/10.1016/j.ijft.2024.100876

ROZINA; EMMANUEL, O.; EZEJI, T. C. Exploring the synergy of nanomaterials and microbial cell factories during biohydrogen and biobutanol production from different carbon sources. **Sustainable Chemistry for the Environment**, v. 6, e100098, 2024. https://doi.org/10.1016/j.scenv.2024.100098

SHARMA, A. K.; KUMAR GHODKE, P.; GOYAL, N.; NETHAJI, S.; CHEN, W. H. Machine learning technology in biohydrogen production from agriculture waste: Recent advances and future perspectives. **Bioresource Technology**, v. 364, e128076, 2022. https://doi.org/10.1016/j.biortech.2022.128076

SILVA, G. O. R.; CARPANEZ, T. G.; DOS SANTOS, C. R.; CASELLA, G. S.; MOREIRA, V. R.; DE PAULA, E. C.; AMARAL, M. C. S. Biohydrogen production from wastewater: Production technologies, environmental and economic aspects. **Journal of Environmental Chemical Engineering**, v. 12, n. 5, e114104, 2024. https://doi.org/10.1016/j.jece.2024.114104

SINGH, T.; SEHGAL, A.; SINGH, R.; SHARMA, S.; PAL, D. B.; TASHKANDI, H. M.; RADDADI, R.; HARAKEH, S.; HAQUE, S.; SRIVASTAVA, M.; ALY HASSAN, A.; SRIVASTAVA, N.; GUPTA, V. K. Algal biohydrogen production: Impact of biodiversity and nanomaterials induction. **Renewable and Sustainable Energy Reviews**, v. 183, e113389, 2023. https://doi.org/10.1016/j.rser.2023.113389

SRIVASTAVA, N.; SINGH, R.; LAL, B.; HAQUE, S. Evaluation of bioprocess parameters for pilot scale fermentative biohydrogen production using organic waste: Environmental remediation, techno-economic challenges & future solutions. **International Journal of Hydrogen Energy**, In Press, e211, 2024. https://doi.org/10.1016/j.ijhydene.2024.05.211

SULTANA, N.; HOSSAIN, S. M. Z.; ALJAMEEL, S. S.; OMRAN, M. E.; RAZZAK, S. A.; HAQ, B.; HOSSAIN, M. M. Biohydrogen from food waste: Modeling and estimation by machine learning based super learner approach. **International Journal of Hydrogen Energy**, v. 48, n. 49, p. 18586-18600, 2023. https://doi.org/10.1016/j.ijhydene.2023.01.339

TAGNE, R. F. T.; COSTA, P.; CASELLA, S.; FAVARO, L. Optimisation of biohydrogen production by dark fermentation of African food-processing waste streams. **International Journal of Hydrogen Energy**, v. 49, p. 266-276, 2024. https://doi.org/10.1016/j.ijhydene.2023.07.348

THIRUMALAIVASAN, N.; NANGAN, S.; KANAGARAJ, K.; RAJENDRAN, S. Assessment of sustainability and environmental impacts of renewable energies: focusing on biogas and biohydrogen (biofuels) production. **Process Safety and Environmental Protection**, v.189, p. 467-485, 2024. https://doi.org/10.1016/j.psep.2024.06.063

UMER, M.; BRANDONI, C.; TRETSIAKOVA, S.; HEWITT, N.; DUNLOP, P.; MOKIM, M. D.; ZHANG, K.; HUANG, Y. Hydrogen production through polyoxometalate catalyzed electrolysis from biomass components and food waste. **Results in Engineering**, v. 23, e102803, 2024. https://doi.org/10.1016/j.rineng.2024.102803

UMUNNAWUIKE, C.; MAHAT, S. Q. A.; NWAICHI, P. I.; MONEY, B.; AGI, A. Biohydrogen production for the sustainable energy transition: A bibliometric and systematic review of the reaction mechanisms, challenges, knowledge gaps and emerging trends. **Biomass and Bioenergy**, v. 188, e107345, 2024. https://doi.org/10.1016/j.biombioe.2024.107345

VINAYAGAM, M.; GRACE, L. K. J.; RANJIT, P. S.; PARIKH, S.; VENKATESH, R.; SOUDAGAR, M. E. M.; AL OBAID, S.; ALHARBI, S. A.; RAMACHANDARAMURTHY, V. K. Synergistic development of nonvascular species microalgae for bio-hydrogen production featured with nano titanium dioxide additive. **Process Safety and Environmental Protection**, In Press, 2024. https://doi.org/10.1016/j.psep.2024.02.080

YÖRÜKLÜ, H. C.; COŞKUNER FILIZ, B.; KANTÜRK FIGEN, A.; ÖZKAYA, B. A multi-criteria decision-making analysis for feasibility of nanoparticle addition in biohydrogen production enhancement for scaling-up studies. **International Journal of Hydrogen Energy**, v. 48, n. 60, p. 22865-22874, 2023. https://doi.org/10.1016/j.ijhydene.2022.11.281

ZAIDI, A. A.; KHAN, S. Z.; ALMOHAMADI, H.; REHAN, M.; QYYUM, M. A. Co-production and enhancement of biogas and biohydrogen by optimizing NaOH-urea pretreatment conditions for kitchen waste. **Process Safety and Environmental Protection**, v. 190, p. 902-912, 2024. https://doi.org/10.1016/j.psep.2024.05.140

Acknowledgments: The authors gratefully acknowledge the reviewers for their invaluable insights.

Authors' contributions: Conceptualization, B.I.; methodology, B.I. and S.S.; validation, M.A.B..; formal analysis, B.I. and M.A.B..; writing - original draft preparation, B.I. and M.A.B.; writing - review and editing, B.I. and S.S.; visualization, B.I. and M.A.B.

Funding: This research did not receive a specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability: The data from this research may be obtained upon request to the corresponding author via e-mail.

Conflict of interest: The authors declare no conflict of interest.