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Fallen leaves to sustainable energy solution: review on hydrogen production

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Fallen leaves represent a significant feedstock for hydrogen production due to their high cellulose content, abundance, and minimal sulfur content. These characteristics make them suitable for various hydrogen production technologies, including biohydrogen and biomass-derived liquid reforming processes, contributing to sustainable energy production. This comprehensive literature review explores fallen leaves as a low-cost biomass feedstock for hydrogen production in the pursuit of zero-carbon and sustainable energy solutions. Steam methane reforming, while cost-effective and possessing high production capacity, results in substantial carbon emissions. In contrast, electrolysis, leveraging renewable resources, is attractive but requires significant energy input. Biomass gasification and thermochemical processes show promise for sustainable hydrogen production, though further technological advancements are necessary. Additionally, anaerobic fermentation by microorganisms can directly produce hydrogen from biomass (including fallen leaves), offering an energy-efficient method that utilizes organic waste. This review evaluates hydrogen production concerning energy efficiency, economics, and environmental impact. The findings contribute to the global transition from fossil fuels to renewable energy sources, aligning with climate commitments and the goal of carbon neutrality.

Sustainability spotlight

Using fallen leaves for hydrogen production supports SDG 7 by providing reliable, affordable, and modern energy. Despite improvements, the Energy Progress Report 2024 highlights the shortfall in meeting SDG 7 targets by 2030. Expanding energy access, scaling renewables, enhancing efficiency, and increasing financial flows to developing countries are vital. Hydrogen from waste organic matter is crucial for decarbonization and achieving net-zero emissions by 2050, generating clean energy and aiding waste management. Green hydrogen promotes environmental sustainability, economic growth, and social progress, particularly in developing countries, aligning with the UN's Sustainable Development Goals.

1. Introduction

To survive the winter months, trees shed their leaves each fall. At the base of the leaf stem, an abscission layer forms, creating a dense layer of cells that cuts off the veins supplying nutrients and water to the leaves. This process causes the stem to weaken, the leaf to die, and eventually fall from the tree. The colors of fallen leaves—orange, red, yellow, and brown—depend on leaf pigments, precipitation, temperature, and daylight length.

Once on the ground, fallen leaves start to decompose with the help of animals, fungi, and bacteria, transforming into simple water and carbon dioxide, which are fundamental components of the carbon cycle.[1] However, when dead leaves are converted into fertilizer, they release greenhouse gases such as methane, carbon dioxide, and nitrous oxide. If fallen leaves enter waterways, they can degrade water quality, harm aquatic life, and obstruct sunlight. Leaves in water require 200% more oxygen compared to those on land.

Traditional disposal methods for dead leaves include landfilling, composting, and incineration. Landfilling emits refractory leachate and methane, composting is time-consuming, and incineration produces vast amounts of noxious particulates, gases, and carbon dioxide[2] (Fig. 1).

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Achieving sustainable development requires meeting human needs without harming the environment. Considering the drawbacks of traditional techniques, developing effective and ecological approaches for managing fallen leaves is highly advantageous.

The scope of this literature review is to examine hydrogen production through the utilization of biomass, particularly fallen leaves. Often regarded as waste, fallen leaves are renewable and abundant, and can be converted into hydrogen through various processes, supporting sustainable and eco-friendly hydrogen generation technologies. This review will explore these processes, their efficiencies, and their environmental impacts, providing a comprehensive overview of this promising sector. The objectives of this literature review (Fig. 2) include:

- Understanding the role of fallen leaves or biomass in hydrogen production and the fundamental principles involved.
- Evaluating different methods of hydrogen production, analyzing their efficiencies and environmental effects.
- Identifying the limitations and challenges associated with these methods, particularly when using fallen leaves.
- Highlighting recent developments and advancements in hydrogen production.
- Discussing prospects and future research directions in this sector.

Using fallen leaves to produce hydrogen can contribute significantly to the transition to a more sustainable energy system.

The highlights of this study emphasize the potential of converting dead leaves, often considered waste, into valuable energy through hydrogen production. This underscores the importance of fallen leaves as a renewable and sustainable feedstock for biohydrogen production, exploring various methods to generate renewable energy with a focus on sustainability. Utilizing fallen leaves in energy processes not only reduces waste but also promotes sustainability; however the implementation of such systems faces economic, technical, and environmental challenges. The novelty of this research lies in the largely unexplored potential of dead leaves as a feedstock for hydrogen production, particularly through steam

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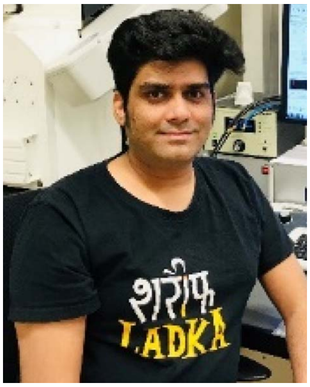

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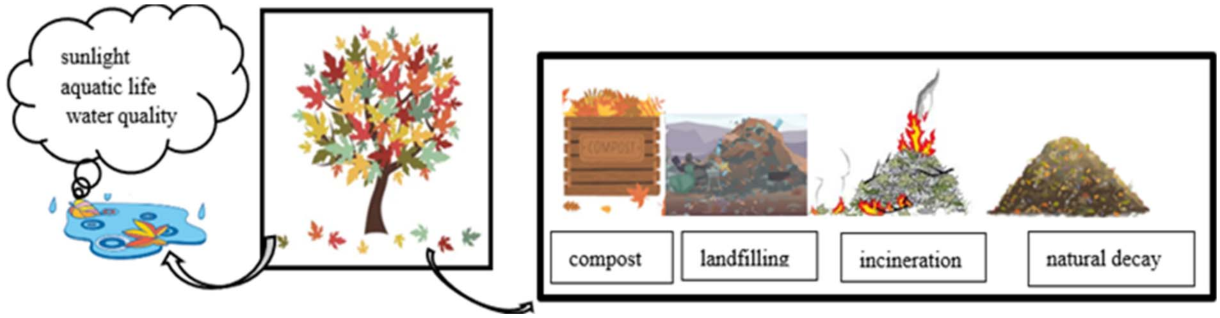

Fig. 1 Waste dead leaves and its consequences.

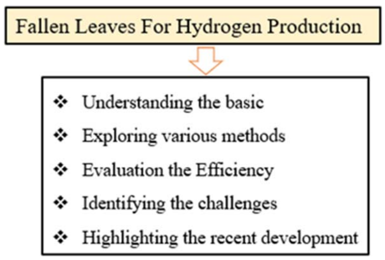

Fig. 2 Objectives of review.

gasification and the integration of advanced methods for utilizing the generated hydrogen. This approach emphasizes environmental friendliness and sustainability, contributing to the global transition towards renewable energy sources. To enhance the introduction, a clearer statement of the novelty and specific contributions compared to existing literature should be included. The utilization of dead leaves as a feedstock for hydrogen production represents a novel approach that has not been extensively explored in the existing literature. This study highlights the potential of steam gasification combined with advanced methods to efficiently convert fallen leaves into hydrogen. The literature review emphasizes the environmental benefits and sustainability of this approach while contributing to the global transition towards renewable energy sources. By addressing the economic, technical, and environmental challenges associated with this process, the study provides valuable insights and practical solutions that can advance the field of renewable energy. This work not only integrates existing knowledge but also introduces new perspectives on the use of biomass for sustainable energy production, making a significant contribution to the literature on renewable energy and waste management.

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2. Innovative energy solutions from fallen leaves

Instead of discarding fallen leaves, numerous methods exist to reprocess them. Currently, dead leaves are used for synthesizing graphene,[3] carbon materials for adsorbing heavy metals and dyes,[4] batteries,[5] supercapacitors,[6] feedstock for biogas production,[7,8] pellets,[9] shrimp preservation,[10] packaging,[11] textiles (fabric, natural dyes, printing on fabric, leather),[12,13] cellulose ethanol,[14] carbon nanotubes,[15] preparation of bio-based reaction mediums, active multifunctional materials such as photocatalysts, bioplastics, and evaporators.[16]

These examples highlight environmentally friendly and innovative ways to utilize dead leaves for energy generation, agricultural purposes, and material creation, contributing to a more circular and sustainable economy. By adopting these methods, we can achieve greater environmental sustainability through the economical treatment of large volumes of fallen leaves (Fig. 3).

The mechanism of converting fallen leaves into energy encompasses various methods, including turning them into organic capacitors, utilizing them as feedstock for biogas generation, and transforming them into other energy storage devices such as supercapacitors and batteries. One promising

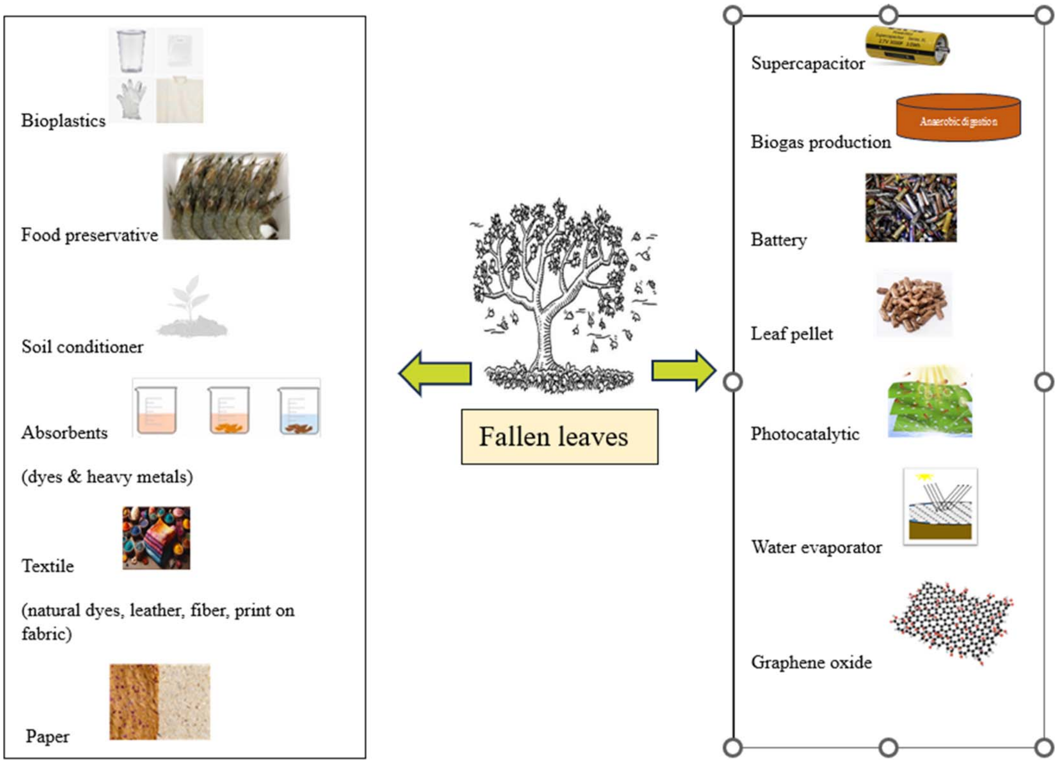

Fig. 3 Application of fallen leaves.

alternative to traditional capacitors is organic capacitors, achieved by introducing a composite material made from graphene oxide and leaf pellets. Graphene oxide provides excellent electrical conductivity, while the leaf pellets offer a high surface area. The combination results in a supercapacitor with both high power density and energy density. This method has been successfully demonstrated by Chinese scientists who innovated supercapacitors from fallen autumn leaves.[17,18]

Moreover, using fallen leaves as feedstock for biogas generation involves breaking down the leaves in an anaerobic digester to generate biogas—a mixture of carbon dioxide and methane that can be used as fuel. This process helps reduce air pollution by preventing the burning of leaves and contributes to a more sustainable energy solution. Additionally, fallen leaves can act as a natural photocatalyst under sunlight to split water into oxygen and hydrogen, providing a sustainable method to produce hydrogen fuel using solar energy. Furthermore, fallen leaves can be converted into pellets, offering a transportable and compact form of biomass-derived energy, thereby contributing to the circular economy.

Converting fallen leaves into energy can have both economic and environmental advantages (Fig. 4). Environmentally, it supports more efficient waste management by reducing leaf burning and decay. For instance, creating organic capacitors from leaves emits significantly less carbon dioxide, while using dead leaves as feedstock for biogas generation decreases the amount of organic waste in landfills. Economically, in Amiens, France, a mechanization factory converts fallen leaves into biogas to power homes in the region. The more energy and biogas generated at the plant, the lower the community's treatment costs, with the potential for buses to run entirely on biogas in the future, reducing reliance on electricity imports and fossil fuels.[19,20]

The quest for efficient, clean, and sustainable energy production is one of the most pressing challenges, with hydrogen often regarded as the “fuel of the future.” When utilized in fuel cells, hydrogen generates water as the only byproduct, making it a truly clean energy source. However, hydrogen production is a complex process and often relies on fossil fuels, which can mitigate its environmental benefits. Various methods exist, including conventional ones like electrolysis and steam methane reforming (SMR), as well as renewable methods such as thermolysis, biological methods, and photolysis.[21,22] Each method has its strengths and weaknesses. SMR is cost-effective but requires carbon capture for emission reduction, while electrolysis produces renewable hydrogen but is energy-intensive. Renewable technologies including biological and photolysis methods, show promise for sustainable hydrogen generation. These diverse strategies contribute to the evolving landscape of hydrogen production, paving the way for a cleaner, greener future.[23–25]

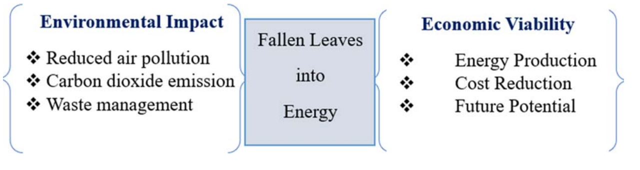

Fig. 4 Perspectives of environment and economic turning fallen leaves into energy.

3. Advancement in hydrogen production from fallen leaves

The utilization of biomass, particularly fallen leaves often recognized as waste, is renewable and abundant. These leaves can be transformed into hydrogen gas through various processes, promoting eco-friendly and sustainable methods for hydrogen production. The most interesting methods for converting fallen leaves into hydrogen involve biohydrogen production and multifunctional development (Table 1). Fallen leaves, especially from species such as Mango, Mahogany, and Teak, have a high potential for biogas and biohydrogen production due to their favorable chemical composition. Co-fermentation of fallen leaves with sewage sludge provides a feasible technique for sustainable hydrogen production using waste biomass.

The water extracts from teak leaf ash (WET) introduce a green material for utilizing fallen leaves in chemical processes. Scientists in Germany have demonstrated the use of autumn tree leaves as feedstock for hydrogen production.[27] The optimal mixing ratio of fallen leaves to sewage sludge was observed to be 20 : 80 (on a volatile solids basis), yielding 37.8 mL per g-VS_{added} of biohydrogen, which is significantly higher compared to the mono-fermentation of fallen leaves (30.5 mL per g-VS_{added}) or the mono-fermentation of sewage sludge (10.3 mL per g-VS_{added}).[28,29]

Under visible light and sunlight irradiation, the active multifunctional material derived from fallen leaves exhibits high performance in photocatalytic hydrogen production. The hydrogen production rate over the active material reached 12.4 μmol h^{-1} cm^{-2} under simulated sunlight (1 kW m^{-2}), which is 4.2 times higher than that of the original fallen leaves. Even under visible light (λ > 400 nm, 0.85 kW m^{-2}), the hydrogen generation rate reached 8.4 μmol h^{-1} cm^{-2}, demonstrating the material's visible-light-responsive photocatalytic activity.

The conversion of fallen leaves into hydrogen as biobased reaction materials primarily involves thermochemical and biological processes (Table 2). Enzymatic hydrolysis, utilizing ligninases and cellulases, efficiently breaks down fallen leaves into sugars for hydrogen production, preserving sugar integrity and avoiding inhibitory byproducts. However, challenges such as enzyme stability and cost remain. Advances in enzyme technology and biomass pre-treatment methods aim to increase sugar yields and hydrogen production potential.

In anaerobic digestion, various factors influence the rate of hydrogen production, including microbial community composition, biomass composition, and digester conditions. Strategies to enhance hydrogen concentration include inhibiting hydrogen-consuming microorganisms and continuously removing hydrogen to maximize production efficiency.

Photo-fermentation shows promise for sustainable hydrogen production but faces challenges related to economic viability and scalability. Optimization of biomass pre-treatment and fermentation conditions—such as substrate concentration, pH, and fermentation modes—is ongoing to improve competitiveness for large-scale hydrogen production.

Dark fermentation offers a flexible biohydrogen production technique that operates without light and can utilize various biomass sources. However, separating hydrogen from other gases generated adds complexity and cost. Research focuses on enhancing yield and efficiency through process optimization and genetic engineering.[30–33]

Supercritical water gasification (SCWG), pyrolysis, and gasification are advanced techniques for hydrogen production from biomass. Gasification is efficient for large-scale applications but requires sophisticated equipment and high temperatures. Pyrolysis offers flexibility and produces multiple products, but it requires further purification for hydrogen extraction. SCWG shows promise for wet biomass and generates hydrogen-rich syngas but it requires ongoing development to address complexity, cost, and sustainability challenges.

Each method represents a pathway toward sustainable hydrogen production, with ongoing research aimed at enhancing efficiency, reducing costs, and advancing environmental sustainability.[34,37–39]

Collecting fallen leaves presents several challenges, including the effort and time required for raking and collection, the environmental impact of using power tools or disposing of leaves in landfills, and potential negative effects on wildlife habitats and soil health if leaves are removed from gardens. However, there are also advantages to collecting fallen leaves, such as reducing landfill waste, improving soil health by adding organic matter, and preventing the smothering of small plants in garden beds.

Table 1 Hydrogen production methods from fallen leaves

Methods	Advantages	Disadvantages	References
Multifunctional material development	Diversifies the utilization of dead leaves beyond conventional waste	Based on the specific processing methods and applications, yield and efficiency may vary; need specialized equipment	12
Biohydrogen production	Co-fermentation of fallen leaves with sewage sludge offers a feasible method for hydrogen generation. Contributes to sustainable energy production by utilizing waste biomass for hydrogen production	The process may require careful optimization to achieve high hydrogen yields. Challenges related to scalability and cost-effectiveness may need to be addressed for large-scale implementation	26

Table 2 Techniques for the conversion of fallen leaves into hydrogen

Method	Advantages	Disadvantages	References
Enzymatic hydrolysis	High specificity for lignin and cellulose breakdown; operated under mild circumstances; produces fermentable sugars for hydrogen generation	Expensive enzymes; enzymes challenges under operational conditions; require pretreatment biomass to enhance efficiency	30
Anaerobic digestion	Low energy and low-cost requirements; apply organic waste as feedstock; generate biogas with high hydrogen composition	Slow rate of hydrogen generation compared to other techniques; require pre-treatment of biomass; process optimization needed for higher yields	31
Photo-fermentation	Uses renewable solar energy; clean process with no toxic emission; can be combined with waste management	Require consistent and strong light resources; basically, lower hydrogen yields than other methods; needs artificial lighting systems	32
Dark-fermentation	No need for light, faster than anaerobic digestion, can handle different conditions; can process a wide range of biomass types	Separating hydrogen from other gases generated can be complicated; lower hydrogen yields than other methods; by-products may need further treatment	33
Supercritical water gasification	Process wet biomass without the need for drying; generates hydrogen-rich syngas; high gasification efficiency and hydrogen selectivity	Still in the experimental stage needs high temperature and pressure; needs further improvement to become commercially viable	34, 35 and 36
Pyrolysis	Can use a wide range of biomass types; produces multiple valuable products (bio-oil, char, hydrogen); flexible and can be combined into existing waste management systems	The quality of hydrogen can be different, requiring purification; high temperatures needed that may enhance energy consumption; the equipment and process can be costly and complex	37
Gasification	Efficient conversion of large amounts of biomass materials; produces a versatile syngas reasonable for different applications; can combine with carbon capture for cleaner energy	Requires high temperatures, enhancing energy input; requires sophisticated and expensive; may generate greenhouse gases if not managed properly	38 and 39

Promoting sustainable leaf disposal and collection involves implementing mechanical leaf collection in areas with heavy leaf accumulation, organizing drop-off events for bagged leaves, and establishing composting programs to divert organic waste from landfills. These practices aim to enhance waste management methods, support sustainable energy production, and preserve wildlife habitats and local ecosystems.

To provide a comprehensive understanding of hydrogen production, it is essential to compare various methods in terms of operating conditions, performance metrics, and challenges. Steam Methane Reforming (SMR) operates at high temperatures (700–1000 °C) and pressures, yielding high amounts of hydrogen but also significant CO_2 emissions, as it requires fossil fuels. Electrolysis, which splits water into hydrogen and oxygen using electricity, produces high-purity hydrogen, with efficiency depending on the electricity source. However, it faces challenges of high energy consumption and cost variability based on electricity prices. Biomass gasification operates at high temperatures (800–1000 °C) with a gasifying agent, offering a renewable hydrogen source with moderate efficiency. However it is challenged by feedstock variability, tar formation, and the need for gas cleanup. Photocatalytic water splitting utilizes sunlight and photocatalysts to separate water into hydrogen and oxygen. Currently, it exhibits low efficiency and is still in experimental stage, with the main challenge being the development of efficient and stable photocatalysts.[32] Hydrogen production from fallen leaves involves processes like pyrolysis or fermentation, utilizing waste biomass and offering potential for carbon-neutral production, but it faces challenges in technology development, feedstock collection, and processing. By comparing these methods, the manuscript can highlight the advantages and limitations of each approach, ultimately providing a clearer picture of the feasibility and sustainability of hydrogen production from fallen leaves.[37]

Promoting sustainable leaf collection and disposal involves implementing mechanical leaf collection in areas with heavy leaf accumulation, organizing drop-off events for bagged leaves, and estabilishing composting programs to reduce landfill waste. These initiatives can support sustainable energy production and improve waste management practices, while also benefiting local ecosystems and wildlife habitats.[40–42]

The advantages of using fallen leaves for hydrogen production, compared to other renewable biomass sources, include availability, reduced waste, lower water usage, enhanced hydrogen generation efficiency, versatility, lower energy input, and reduced greenhouse gas emissions. Fallen leaves are widely available, making them readily accessible for biomass-based hydrogen production. Their utilization can decrease waste and enhance rural livelihoods, contributing to overall energy security.

Dry anaerobic fermentation of fallen leaves requires less water compared to wet anaerobic fermentation, making it a more sustainable and efficient process. Additionally, synergistic dry fermentation of fallen leaves with other waste materials, such as garden or food waste, can further enhance hydrogen generation efficiency. This approach offers flexibility in hydrogen production methods, either using fallen leaves as a sole substrate or co-fermenting them with other waste materials.

Moreover, fallen leaves require lower energy input than other biomass sources, making them a cost-effective and sustainable option for hydrogen production. Utilizing sustainable and renewable biomass sources also contributes to reducing greenhouse gas emissions.[10]

The age of fallen leaves can affect their suitability for hydrogen production. Older leaves can convert more easily into simple sugars; however as leaves age, their lignin content

Table 3 Author's contributions to various hydrogen production methods

Document	Contribution	Review focus	References
A concise review of recent biohydrogen production technologies	This review provides an overview of the latest advancements in biohydrogen production technologies, highlighting the efficiency, scalability, and sustainability of different methods	The paper discusses various biohydrogen production methods, including dark fermentation, photo fermentation, and microbial electrolysis cells, emphasizing their potential for sustainable energy production	35
Hydrogen roadmap Europe: a sustainable pathway for the European energy transition	This roadmap outlines a strategic plan for the large-scale deployment of hydrogen and fuel cells across Europe, aiming to achieve a sustainable energy transition	The document focuses on the socio-economic impacts of hydrogen adoption, the necessary infrastructure developments, and policy recommendations to support the hydrogen economy	36
A comprehensive review on hydrogen production and utilization in North America: prospects and challenges	This comprehensive review analyzes the current state and future prospects of hydrogen production and utilization in North America, addressing technological, economic, and policy challenges	The review covers various hydrogen production methods, including steam methane reforming, electrolysis, and biomass gasification, and discusses their feasibility, efficiency, and environmental impacts	43
Feasibility analysis of green hydrogen production from oceanic energy	This study evaluates the technical, economic, and environmental feasibility of producing green hydrogen using oceanic energy sources, such as offshore wind and wave energy	The analysis includes a detailed assessment of the potential for integrating oceanic energy with hydrogen production technologies, highlighting the benefits and challenges of this approach	44
Comparison of biohydrogen production processes	This paper compares different biohydrogen production processes, providing insights into their efficiency, scalability, and environmental impacts	The comparison includes dark fermentation, photo fermentation, two-stage processes, and biocatalyzed electrolysis, with a focus on optimizing conditions for maximum hydrogen yield	45
Hydrogen production from biomass through integration of anaerobic digestion and biogas dry reforming	This review explores the integration of anaerobic digestion and biogas dry reforming for hydrogen production, emphasizing the potential for utilizing biomass waste	The paper discusses the technical and economic aspects of combining these processes, including the challenges of feedstock variability and gas cleanup requirements	46
Hydrogen production from phototrophic microorganisms: reality and perspectives	This review examines the potential of phototrophic microorganisms for hydrogen production, discussing the current state of research and future perspectives	The focus is on the biological mechanisms of hydrogen production in phototrophic microorganisms, the efficiency of different species, and the challenges of scaling up these processes for industrial applications	47

increases, making them more resistant to pretreatment. Components like xylan, cellulose, and arabinan (a type of hemicellulose in plant cell walls) are crucial for hydrogen production and can be transformed into simple sugars through pretreatment processes.[11,12]

The following documents collectively provide a comprehensive overview of various hydrogen production methods, highlighting their advantages, limitations, and potential for integration with sustainable practices (Table 3).

To evaluate the hydrogen production potential from fallen leaves, a detailed methodology is essential. Initially, fallen leaves are collected from various locations to ensure a diverse sample, sorted to remove non-leaf material, air-dried to reduce moisture content, and ground into a fine powder to increase surface area for better reaction efficiency. The leaf biomass is then characterized through proximate analysis to determine moisture, volatile matter, ash content, and fixed carbon, ultimate analysis to measure elemental composition (carbon, hydrogen, nitrogen, sulfur, and oxygen), and calorific value assessment using a bomb calorimeter. For hydrogen production, two processes are employed: pyrolysis and fermentation. In pyrolysis, a reactor heats the leaf biomass in the absence of oxygen, gradually increasing the temperature to 500–700 °C, with gaseous products collected and analyzed for hydrogen content using gas chromatography. In fermentation, anaerobic fermentation is conducted in a bioreactor with specific microbial cultures, where the leaf biomass is mixed with water and inoculated with microbes. The temperature is maintained at 30–37 °C, and the biogas produced is collected and analyzed for hydrogen content using gas chromatography. Data analysis involves calculating the hydrogen yield per unit mass of leaf biomass, evaluating energy efficiency by comparing the energy content of the produced hydrogen with the energy input, and assessing environmental impact by analyzing by-products and emissions. Optimization is achieved by varying parameters such as temperature, pressure, and microbial culture to optimize hydrogen yield, and using statistical tools to analyze the data and determine the optimal conditions for maximum hydrogen production. This comprehensive methodology ensures a clear and detailed evaluation of the hydrogen production potential from fallen leaves.[48]

To determine the hydrogen yield from a known quantity of leaf biomass, follow this detailed process:

Step 1: weigh the leaf biomass.

Measure the initial mass of the dried and ground leaf biomass, denoting it as m_{biomass} (in grams).

Step 2: collect the produced hydrogen.

During the hydrogen production process (such as pyrolysis or fermentation), collect the hydrogen gas produced. Ensure that the collection system is sealed and calibrated to prevent gas loss because hydrogen is highly combustible.

Step 3: measure the volume of hydrogen.

Utilize a gas collection system, like a gas syringe or flow meter, to measure the volume of hydrogen gas produced, denoted as V_{H_2} (in liters).

Step 4: standardize the conditions.

Make sure the volume of hydrogen gas is measured under standard temperature and pressure (STP) conditions (0 °C and 1 atm). If measurements are taken under different conditions, convert the measured volume to STP using the ideal gas law.

Step 5: calculate the moles of hydrogen.

Use the ideal gas law, $PV = nRT$, to calculate the number of moles of hydrogen gas produced.[49] Rearranging gives:

$$n = \frac{PV}{RT} \tag{1}$$

At STP, where R = ideal gas constant, $P = 1$ atm and $T = 273.15$, this simplifies to:

$$n = \frac{V_{H_2}}{22.414} \tag{2}$$

where 22.414 L is the molar volume of an ideal gas at STP.

Step 6: calculate the hydrogen yield.

Hydrogen yield is the amount of hydrogen produced per unit mass of leaf biomass, calculated using the formula:

$$\text{Hydrogen yield} = \frac{n \times M_{H_2}}{m_{\text{biomass}}} \tag{3}$$

where, n is the number of moles of hydrogen. M_{H_2} is the molar mass of hydrogen (2.016 g mol^{-1}). m_{biomass} is the mass of the leaf biomass (in grams).

This can be simplified to:

$$\text{Hydrogen yield} = \frac{V_{H_2} \times 2.016}{22.414 \times m_{\text{biomass}}} \tag{4}$$

By following these steps, it can accurately calculate the hydrogen yield from the leaf biomass, which is essential for evaluating the efficiency of hydrogen production processes from biomass sources.

To evaluate the energy efficiency of the hydrogen production process, need to compare the energy content of the produced hydrogen with the total energy input required for the process.

Step 1: determine the energy content of produced hydrogen.

Calculate the total amount of hydrogen produced:

• Measure the total mass of hydrogen produced, denoted as mH_2 (in kilograms).

Use the Lower Heating Value (LHV) or Higher Heating Value (HHV):

• The LHV of hydrogen is approximately 120 MJ kg^{-1}.
• The HHV of hydrogen is approximately 142 MJ kg^{-1}.

Calculate the energy content:

• Use the formula:

$$EH_2 = mH_2 \times \text{LHV or HHV}EH_2 = mH_2 \times \text{LHV or HHV}$$

• For example, if you produced 1 kg of hydrogen using LHV:

$$EH_2 = 1\text{ kg} \times 120\text{ MJ kg}^{-1} = 120\text{ MJ}$$

Step 2: calculate the total energy input.

Identify all energy inputs required for the hydrogen production process, including:

• Thermal energy: energy required to heat the biomass (*e.g.*, in pyrolysis).

• Electrical energy: energy required for equipment operation (*e.g.*, grinding, pumping, fermentation).

• Chemical energy: energy content of any additional reactants used.

Example calculation of total energy input:

• Thermal energy: 200 MJ.

• Electrical energy: 50 MJ.

• Chemical energy: 30 MJ.

Sum all these energy inputs:

$$E_{\text{input}} = 200\ \text{MJ} + 50\ \text{MJ} + 30\ \text{MJ} = 280\ \text{MJ}$$

Step 3: calculate energy efficiency.

Energy efficiency (η) of the hydrogen production process is calculated using the formula:

$$\eta = \frac{E_{\text{H}_2}}{E_{\text{Input}}} \times 100\% \tag{5}$$

Example calculation of energy efficiency:

Using the previously calculated values:

• Energy content of produced hydrogen: 120 MJ.

• Total energy input: 280 MJ.

Substituting these values into the formula:

$$\eta = \frac{120\ \text{MJ}}{280\ \text{MJ}} \times 100\% = 42.86\%$$

In this example, the energy efficiency of the hydrogen production process is 42.86%. This means that 42.86% of the input energy is converted into useful hydrogen energy.

By following these steps, one can accurately evaluate the energy efficiency of the hydrogen production process, which is crucial for assessing the viability and sustainability of hydrogen as an energy source.[50–53]

The comprehensive statistical analyses aims to evaluate the hydrogen production potential from fallen leaves. Utilizing statistical tools such as analysis of variance (ANOVA) can compare the hydrogen yields and efficiencies of different hydrogen production methods, including pyrolysis and fermentation of fallen leaves, to determine if there are statistically significant differences between the methods.[54] Regression analysis can be applied to understand the relationship between various process parameters (*e.g.*, temperature, pressure, biomass particle size) and hydrogen yield, identifying key factors that influence hydrogen production efficiency and quantifying their impact. For instance, a multiple regression model can predict hydrogen yield based on the combined effects of temperature and pressure during pyrolysis. Sensitivity analysis can identify the most critical factors affecting hydrogen production efficiency by systematically varying process parameters to assess their influence on the output, highlighting which parameters have the greatest impact on hydrogen yield and energy efficiency. For example, varying the temperature and residence time in the pyrolysis process can reveal their relative importance in maximizing hydrogen production. The following steps can be taken for hydrogen production from fallen leaves: gather experimental data on hydrogen yields and process parameters from multiple trials of pyrolysis and fermentation; perform ANOVA to compare the mean hydrogen yields of pyrolysis and fermentation, testing the hypothesis that there are significant differences between the methods; develop a regression model to predict hydrogen yield based on key process parameters (*e.g.*, temperature, pressure) and analyze the regression coefficients to understand the relative importance of each parameter; and conduct sensitivity analysis by varying one parameter at a time (*e.g.*, temperature) while keeping others constant, measuring the resulting changes in hydrogen yield, and extending this to multi-parameter sensitivity analysis to capture interactions between parameters. Incorporating these statistical analyses will provide a more rigorous and quantitative evaluation of hydrogen production from fallen leaves. This approach enhances the manuscript by offering deeper insights into the factors influencing hydrogen yield and efficiency, thereby supporting the feasibility and optimization of this sustainable energy production method. By including these detailed statistical analyses, the manuscript will present a comprehensive and scientifically robust evaluation of hydrogen production from fallen leaves, contributing valuable knowledge to the field of renewable energy research.[51]

Developing a kinetic model for hydrogen production from fallen leaves involves understanding the chemical reactions and processes that convert biomass into hydrogen. The primary reactions in the pyrolysis or gasification of fallen leaves include the breakdown of cellulose, hemicellulose, and lignin into smaller molecules, followed by further reactions to produce hydrogen, carbon monoxide, and other gases. Identifying the rate-controlling steps in these reactions is crucial, as the decomposition of cellulose might be slower than the subsequent gas-phase reactions, making it the rate-limiting step. Determining the activation energy for each reaction step helps in understanding the temperature dependence of the reaction rates, and reaction rate constants, which can be determined experimentally or through computational methods, are essential for modeling the kinetics of the process. There are different modeling approaches to consider. Detailed kinetic models include all the individual reaction steps and species involved, offering high accuracy but being computationally intensive. On the other hand, global kinetic models simplify the process by combining multiple steps into a single overall reaction, making them less accurate but easier to use for large-scale simulations. Conducting pilot-scale experiments helps validate the kinetic model and ensures it accurately represents the real-world process. Sensitivity analysis identifies which parameters have the most significant impact on the model's predictions, helping to focus further research and optimization efforts.

A simplified global kinetic model for the pyrolysis of fallen leaves might look like this:

$$\text{Leaves} \rightarrow \text{char} + \text{volatiles}$$

$$\text{Volatiles} \rightarrow H_2 + CO + CO_2 + CH_4$$

The rate of hydrogen production can be expressed as:[52]

$$r_{H_2} = k \cdot [\text{volatiles}] \cdot e^{-\text{RTEa}}$$

where: r_{H_2} is the rate of hydrogen production. k is the pre-exponential factor. E_a is the activation energy. R is the universal gas constant. T is the temperature.

Additional considerations include feedstock variability, as the chemical composition of fallen leaves varies by tree species, season, and location, affecting hydrogen yield and process efficiency. Effective pre-treatment methods like drying, grinding, and homogenizing can help standardize feedstock quality for consistent hydrogen production. Different catalysts can significantly influence the efficiency and yield of hydrogen production from fallen leaves, and research into optimal catalysts is ongoing and crucial for improving overall efficiency. By-products such as biochar from pyrolysis can be sold as soil amendments or for carbon sequestration credits, potentially offsetting some production costs.[52]

This LCA should evaluate the environmental impacts of each method, including greenhouse gas emissions, energy consumption, and resource use. For instance, traditional methods like steam methane reforming typically have high carbon footprints, averaging around 11 kg CO_{2eq} per kg H_2. In contrast, hydrogen production from renewable sources, such as water electrolysis powered by renewable energy, can significantly reduce emissions, with some methods achieving as low as 2.02 kg CO_{2eq}/kg H_2.[52] The LCA should also consider other environmental factors, such as acidification potential and abiotic depletion potential. For example, biomass gasification, which includes the use of fallen leaves, can offer lower greenhouse gas emissions compared to traditional methods. By systematically comparing these factors, the LCA can provide a comprehensive understanding of the sustainability of hydrogen production from fallen leaves *versus* traditional methods, highlighting the potential environmental benefits and trade-offs. Incorporating this detailed LCA will strengthen the manuscript by offering a robust comparison of the environmental performance of different hydrogen production pathways, contributing valuable insights to the field of renewable energy research.[55]

4. Challenges and limitations of fallen leaves in hydrogen production

However, the use of dead leaves for hydrogen production presents several challenges and limitations (Fig. 5). Fallen leaves contain relatively low levels of hydrogen-rich components, particularly xylan and cellulose, which can hinder hydrogen production efficiency. Converting fallen leaves into hydrogen requires multiple steps, including pretreatment, hydrolysis, and fermentation, which are energy-intensive and increase costs.

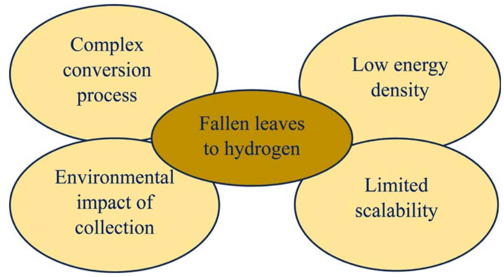

Fig. 5 Challenges and limitations of fallen leaves in hydrogen production.

Additionally, fallen leaves have a low energy density, posing challenges for transport and storage. Moreover, utilizing dead leaves for hydrogen production faces scalability difficulties due to their limited availability and seasonal nature. The collection of fallen leaves for hydrogen production can also have negative environmental impacts, like disrupting wildlife habitats and contributing to soil erosion.[13]

However, commercializing this technology faces challenges due to the natural variability in fallen leaves. Despite these obstacles, converting dead leaves into energy represents a promising avenue for sustainable energy production. It is essential to note that the success of such initiatives depends on various factors, including local environmental conditions, technological advancements, and policy support.

Commercializing the production of organic capacitors, for instance, can be challenging due to the natural variability in leaves, as highlighted by Fred Cannon at Penn State University.[56] Efficiently utilizing dead leaves as a material without compromising their biocomponents is another challenge, as discussed in a study published in *Nature Communications*.[57]

Technological advancements can significantly improve the collection, transportation, and processing of leaves. Advanced sensors and automation systems can optimize the collection and transportation of fallen leaves, reducing the need for manual labor and increasing efficiency. Moreover, new processing technologies, such as anaerobic digestion and enzymatic hydrolysis, can enhance the cost-efficiency and effectiveness of converting leaves into biogas and other forms of energy. Improving sustainable energy production methods, including converting dead leaves into energy, is crucial for reducing greenhouse gas emissions, enhancing energy security, and facilitating the transition to a more sustainable energy system.[58]

To ensure that the collection of fallen leaves for hydrogen production is environmentally sustainable, it is essential to adopt practices that minimize disruption to wildlife habitats and prevent soil erosion. Implementing selective collection practices can help preserve critical habitats by leaving leaf piles in areas known to be habitats for insects, small mammals, and other wildlife, providing necessary shelter and food sources. Timing the collection of leaves to avoid critical periods for wildlife, such as breeding or hibernation seasons, can reduce the impact on local fauna. Establishing buffer zones where leaf collection is restricted can protect sensitive areas and allow wildlife to thrive undisturbed. Using collected leaves as mulch can protect soil from erosion by reducing the impact of rainfall and wind, while also helping to retain soil moisture and improve soil structure. Collecting leaves along the natural contours of the land can help prevent soil erosion by maintaining the natural flow of water and reducing runoff. Planting cover crops in areas where leaves are collected can help stabilize the soil, reduce erosion, and improve soil health through the addition of organic matter. Integrating leaf collection with agroforestry practices can enhance biodiversity and soil health, as trees and shrubs can provide additional habitats for wildlife and help prevent soil erosion. Engaging local communities in sustainable collection practices can ensure that traditional knowledge and practices are incorporated, promoting environmental stewardship and sustainable land management. By adopting these sustainable collection practices, the environmental impact of leaf collection for hydrogen production can be minimized, ensuring that the process contributes positively to both energy production and ecosystem health.[49]

A comprehensive discussion on overcoming technical barriers in hydrogen production from fallen leaves is essential. The composition and quality of fallen leaves can vary significantly depending on the type of tree, season, and geographic location, affecting the consistency and efficiency of hydrogen production processes. Implementing pre-treatment processes such as drying, grinding, and homogenizing the biomass can help standardize the feedstock. Aditionally, developing robust process control systems that adjust parameters in real-time based on feedstock characteristics can improve consistency. Optimizing the conditions for pyrolysis or fermentation to maximize hydrogen yield is complex due to numerous variables like temperature, pressure, and residence time. Conducting extensive experimental studies and using advanced modeling techniques like response surface methodology (RSM) can help identify optimal conditions. Moreover, machine learning algorithms can predict outcomes and optimize process parameters. Efficient catalysts are crucial for enhancing hydrogen yield in both pyrolysis and fermentation processes, but developing cost-effective and durable catalysts remains a challenge. Research and development efforts should focus on discovering new catalyst materials that are both effective and economical, and improving the regeneration and recycling of catalysts can reduce costs and enhance sustainability. Scaling up laboratory-scale processes to industrial levels introduces new technical challenges, such as maintaining uniform temperature and pressure conditions and handling large volumes of biomass. Pilot-scale studies are essential to identify and address scale-up issues, and developing modular and scalable reactor designs can facilitate the transition from lab to industrial scale. Integrating hydrogen production with existing biomass processing facilities can also improve efficiency and reduce costs. The energy required for processes like pyrolysis can be substantial, impacting the overall energy efficiency and economic viability of hydrogen production from fallen leaves. Implementing energy recovery systems, such as using the heat generated during pyrolysis to preheat the biomass, can improve energy efficiency, and exploring alternative energy sources, such as solar or waste heat, can further reduce energy consumption. Managing by-products like biochar and liquid residues can be challenging, especially in terms of disposal or finding valuable applications. Developing value-added applications for by-products, such as using biochar for soil amendment or carbon sequestration, can create additional revenue streams and reduce waste, and researching and developing methods to treat and utilize liquid residues can enhance sustainability. Navigating regulatory requirements and market acceptance for hydrogen produced from biomass can be complex and time-consuming. Engaging with regulatory bodies early in the development process can help ensure compliance and streamline approvals, and building partnerships with industry stakeholders and conducting market research can facilitate market entry and acceptance. By addressing these technical barriers comprehensively, the manuscript will provide a more robust evaluation of the feasibility and potential of hydrogen production from fallen leaves, contributing valuable insights to the field of renewable energy research.[59]

The success of sustainable energy initiatives is greatly influenced by policies. Clear and long-term strategies with defined targets, fiscal and financial incentives, mandates, support for research, development, and demonstration (RD&D), infrastructure investment, and commercialization, as well as training and skills development, public awareness campaigns, and access to reliable information, are all essential policy tools. Effective sustainability governance through regulations and certifications is also crucial.

These policies can reduce market risks, encourage investments, streamline permitting and regulatory processes, simplify planning, and address bureaucratic challenges.[60,61]

One notable example is the co-fermentation of sewage sludge and fallen leaves, which produced biohydrogen with a yield of 37.8 mL per g of VS-added. This case study highlights the potential of combining different biomass sources to optimize hydrogen production.[62] The process involves mixing sewage sludge, which is rich in organic matter, with fallen leaves, which provide additional carbon sources. The co-fermentation process not only enhances hydrogen yield but also helps in managing waste more effectively. The synergy between the two biomass sources can lead to improved microbial activity and better substrate utilization, resulting in higher hydrogen production. This approach demonstrates the feasibility of using mixed biomass feedstocks to enhance biohydrogen production, making it a promising strategy for sustainable energy generation. Another successful project involves the integration of biomass gasification with existing waste management systems. Biomass gasification is a thermochemical process that converts organic materials, such as fallen leaves, into hydrogen-rich syngas. This syngas can then be purified to produce hydrogen. Integrating this process with waste management systems can provide several benefits: utilizing fallen leaves and other organic waste materials for hydrogen production helps reduce the volume of waste that needs to be disposed of, addressing waste management challenges; the process of gasification allows for the recovery of energy from waste materials, converting them into valuable hydrogen fuel; by integrating hydrogen production with existing waste management infrastructure, the overall costs can be reduced, and the shared infrastructure and resources can lead to economies of scale, making the process more economically viable; and this approach reduces greenhouse gas emissions by diverting organic waste from landfills and utilizing it for clean energy production, with the lower carbon footprint of biomass gasification compared to traditional hydrogen production methods further enhancing its environmental benefits. A real-world example of this integration is a community-based biomass gasification plant that processes fallen leaves and other organic waste collected from local households and parks. The plant not only produces hydrogen but also generates electricity and heat, which are used to power the facility and supply energy to the local community. The project has been successful in demonstrating the feasibility of small-scale, decentralized hydrogen production from biomass. It has also provided valuable insights into the operational challenges and solutions for integrating biomass gasification with waste management systems. These case studies provide valuable lessons on the scalability and economic viability of hydrogen production from fallen leaves. Key takeaways include ensuring a consistent and reliable supply of biomass feedstock, developing efficient collection and pre-treatment systems to help standardize the feedstock and improve process efficiency, continuous research and development to optimize the conditions for hydrogen production, and the use of advanced modeling and simulation tools to aid in identifying optimal process parameters. Government incentives and subsidies for renewable energy projects can significantly enhance the economic feasibility of hydrogen production from biomass, and policies that support the integration of renewable energy with waste management systems can further drive the adoption of these technologies. Engaging local communities and stakeholders is essential for the success of decentralized hydrogen production projects, as community-based initiatives can foster local support and participation, ensuring the sustainability of the projects.

5. Design thinking for the production of hydrogen from dead leaves

Design thinking, a human-centered approach to innovation combines the possibilities of methods, the needs of people, and the requirements for business success when used to the fallen leaves into hydrogen production, it could include the following route:

• Empathize: in hydrogen production, understanding the needs and challenges of the stakeholders included and then could involve environmentalists, scientists and energy consumers and policymakers.

• Define: identify the problems, we are facing to solve. In this sector, it is going to be "How can we sustainably and efficiently generate hydrogen from dead leaves?"

• Ideate: brainstorm innovative technologies for hydrogen production from dead leaves, which could include seeking different techniques including biological process or artificial leaf technology or thermochemical method, and then consider the strengths and weaknesses of each method.

• Prototype: develop experiment or small-scale model to check your ideas, including setting up a lab experiment to test the efficiency of hydrogen from dead leaves applying the selected method.

• Test: evaluation factors involving the energy needed for the process, the amount of hydrogen produced and environmental effect.

• Implement: if the outcomes are promising, work towards installation of the method on a larger scale, which involves improving collaboration with industry partner or a pilot project.

Overall, design thinking is an iterative process that relies on the results of tests. It often requires revisiting the ideation and prototyping steps to refresh methods.

Key questions include understanding how the variability in the chemical composition of fallen leaves from different tree species affects hydrogen yield and process efficiency and identifying the most effective pre-treatment methods for standardizing feedstock quality. Additionally, determining the optimal conditions (temperature, pressure, residence time) for maximizing hydrogen yield in pyrolysis and fermentation processes, as well as assessing the influence of different catalysts on efficiency and yield, are crucial. Economic feasibility questions should focus on the detailed cost components (CAPEX and OPEX) for setting up and operating hydrogen production facilities using fallen leaves, and the impact of government incentives and subsidies on the overall economic viability. Environmental impact questions should explore the life cycle environmental impacts of hydrogen production from fallen leaves compared to traditional methods, and how integrating hydrogen production with existing waste management systems affects the overall carbon footprint. Recommendations include developing and implementing standardized pre-treatment processes to ensure consistent feedstock quality, conducting comprehensive studies on the chemical composition of fallen leaves from various tree species, investing in advanced process control systems that adjust operational parameters in real-time, and utilizing machine learning algorithms to predict process outcomes and optimize parameters. Catalyst research should focus on discovering and developing cost-effective and durable catalysts and exploring the regeneration and recycling of catalysts to reduce costs and improve sustainability. Pilot-scale studies are essential to identify and address challenges associated with scaling up laboratory processes to industrial levels and developing modular and scalable reactor designs can facilitate the transition from lab to industrial scale. Future research directions should explore the integration of hydrogen production from fallen leaves with renewable energy sources, such as solar or wind, to improve energy efficiency and reduce costs, and investigate the potential of using waste heat from other industrial processes to power hydrogen production facilities. Researching value-added applications for by-products like biochar, developing methods to treat and utilize liquid residues, studying the feasibility and benefits of community-based hydrogen production projects, and engaging with local communities and stakeholders to foster support and participation in decentralized hydrogen production initiatives are also important. Finally, analyzing the impact of existing policies and regulations on the adoption of hydrogen production from biomass, and conducting market research to identify potential barriers and opportunities for the commercialization of hydrogen produced from fallen leaves will provide a comprehensive roadmap for advancing the field, contributing valuable insights to the broader renewable energy research community.[63]

6. Prospects of fallen leaves into hydrogen production

In hydrogen production, the prospects and research directions for utilizing fallen leaves as biomass are quite promising. Future efforts focus on increasing efficiency, scalability, and reducing environmental impact. Research is exploring innovative technologies such as biological processes and biomass gasification, which offer sustainable and environmentally friendly approaches to converting fallen leaves into hydrogen. There is also a critical need for advancing existing technologies and exploring new production methods to improve efficiency.

Additionally, there is potential for integrating hydrogen production from fallen leaves with other renewable energy sources like wind and solar, which could enhance overall sustainability and energy system efficiency. Introducing hydrogen from fallen leaves could contribute to forest management, carbon sequestration, and waste reduction, promoting environmental benefits and advancing circular economy principles.

Future research directions should concentrate on optimizing fallen leaf processing techniques, developing large-scale collection methods, and designing efficient production systems capable of handling large volumes of biomass. Addressing technical challenges associated with these conversion methods will be crucial.

As the transition towards hydrogen from fallen leaves progresses, supportive policies are needed to facilitate leaf collection and utilization, improve hydrogen production infrastructure and storage capabilities, and foster international cooperation to enhance market interoperability and promote sustainable hydrogen adoption.

Overall, the prospects and research directions for integrating fallen leaves into hydrogen technologies aim to enhance sustainability, advance technology, and overcome challenges to fully harness the potential of this valuable renewable energy source.

Hydrogen production from fallen leaves represents an intriguing concept, but specific data or studies on the economic and environmental impacts of hydrogen production from fallen leaves are currently limited (Fig. 6). Economic considerations include biomass processing costs, collection expenses, and infrastructure costs for storage, production, and distribution of hydrogen. The demand for hydrogen, particularly from biomass like dead leaves, is expected to grow, potentially creating a market for hydrogen derived from biomass sources.

Depending on the production techniques used, hydrogen production can result in greenhouse gas emissions, despite hydrogen itself being a clean-burning fuel. The use of fallen leaves for hydrogen production holds potential advantages in terms of resource recycling and waste management. However, emissions of other greenhouse gases such as ozone, methane, and water vapor can contribute to indirect warming effects when hydrogen is released into the atmosphere. Overall, further research is needed to fully understand the economic and environmental impacts of hydrogen production from fallen leaves (Table 4).

Comparing the costs of hydrogen production from fallen leaves with conventional methods is essential for evaluating potential sustainability benefits. This evaluation should cover capital expenditures (CAPEX), operational expenditures (OPEX), and the overall cost per kilogram of hydrogen produced. Traditional methods like steam methane reforming (SMR) have relatively lower initial capital costs due to established technology and infrastructure; however, integrating carbon capture and storage (CCS) to reduce emissions can significantly increase CAPEX. Producing hydrogen *via* electrolysis, especially using renewable energy sources, requires substantial investment in electrolyzers and renewable energy infrastructure, making the CAPEX generally higher than SMR. In contrast, setting up facilities for biomass processing, pyrolysis, or fermentation involves higher initial costs due to the need for specialized equipment for handling and converting biomass into hydrogen. However, advancements in technology and economies of scale can help reduce these costs over time. Operational costs for SMR are heavily influenced by the price of natural gas, which can be volatile, and the costs associated with CCS add to the OPEX. The main operational cost for electrolysis is the electricity required to split water into hydrogen and oxygen, with renewable energy potentially reducing costs in the long term

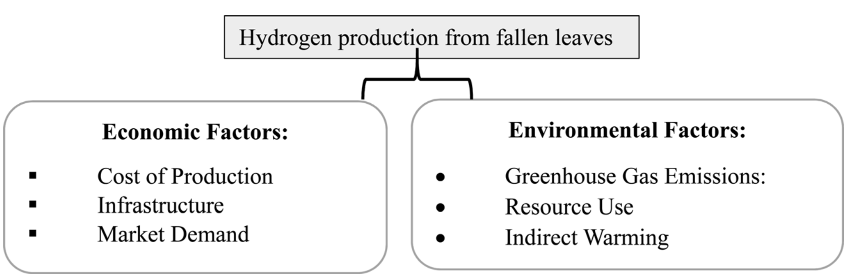

Fig. 6 Economic and environmental factors of hydrogen production from dead leaves.

despite high initial investment. For hydrogen production from fallen leaves, operational costs can be lower if the feedstock is readily available and inexpensive, with process efficiency and scale of production playing crucial roles in determining OPEX. Maintenance of specialized equipment and handling of by-products are additional considerations.[68,69]

The cost of hydrogen production ranges from \$1.00 to \$2.50 per kilogram for SMR, depending on natural gas prices and CCS implementation, and from \$3.00 to \$7.00 per kilogram for electrolysis, influenced by electricity prices and the scale of renewable energy deployment. For pyrolysis and fermentation of fallen leaves, the cost can range from \$2.00 to \$4.00 per kilogram, depending on the efficiency of the conversion process, the availability and cost of biomass, and the scale of operations.[68] Revenue streams from by-products, such as biochar from pyrolysis, which can be sold as a soil amendment or used for carbon sequestration credits, can offset some production costs. Fermentation processes might produce valuable chemicals or biofuels that can be marketed. Government incentives, including subsidies and grants for renewable energy projects and carbon credits for producing hydrogen from renewable sources, can significantly reduce both CAPEX and OPEX, providing an additional revenue stream and making the process more economically viable. Comparing the environmental impact, SMR has a high carbon footprint, averaging around 11 kg CO_{2eq}/kg H_2, while electrolysis using renewable energy can reduce emissions significantly, depending on the energy source. Hydrogen production from biomass, including fallen leaves, generally has a lower carbon footprint, contributing to waste management and reducing environmental impact. While SMR is currently more cost-effective, its environmental impact and reliance on fossil fuels are significant drawbacks. Electrolysis is cleaner but more expensive. Hydrogen production from fallen leaves offers a sustainable alternative with potential cost savings in the long term, especially with technological advancements and government support. The economic feasibility improves with the availability of low-cost biomass and additional revenue from by-products and carbon credits. Incorporating this detailed economic evaluation will provide a thorough comparison of the costs associated with different hydrogen production methods, offering valuable insights into the economic feasibility and potential advantages of using fallen leaves as a sustainable feedstock.[67]

Integrating leaf collection with other environmental management practices is a promising area for further research. Collected leaves can be composted to create nutrient-rich soil amendments, improving soil health, reducing the need for chemical fertilizers, and enhancing plant growth. Additionally, leaves can be used to create habitats for various organisms, such as insects and small mammals, thereby promoting biodiversity. They can also serve as mulch to protect soil from erosion, particularly in areas prone to heavy rainfall or wind erosion. By composting leaves and incorporating them into the soil, carbon is sequestered, helping to mitigate climate change. Furthermore, leaf collection can be integrated into Integrated Farm Management (IFM) practices, which combine traditional methods with modern technology to achieve high productivity with low environmental impact. Lastly, leaves can be utilized in rain gardens or other water management systems to help filter and retain water, reducing runoff and improving water quality. Exploring these areas could lead to innovative practices that enhance environmental sustainability and agricultural productivity.[68]

To improve the economic feasibility of hydrogen production from fallen leaves, it is crucial to explore various funding opportunities and partnerships. Government grants and subsidies can provide initial financial support, reducing the burden of infrastructure costs. Many governments offer incentives for renewable energy projects, which can be leveraged to fund the development of hydrogen production facilities. Additionally, international organizations and environmental agencies often have funding programs aimed at promoting sustainable energy solutions. Forming partnerships with private companies can bring in additional resources and expertise. Companies in the automotive, energy, and technology sectors may have a vested interest in sustainable hydrogen production and could provide financial backing, technical support, and market access. Collaborations with these industries can also lead to the development of innovative technologies and processes, further enhancing the efficiency and cost-effectiveness of hydrogen production. Partnering with research institutions and universities can provide access to cutting-edge research, skilled personnel, and advanced facilities. These partnerships can facilitate the development of new technologies and processes for hydrogen production, as well as provide opportunities for joint funding applications. Academic institutions often have access to research grants and funding

Table 4 Economic and environmental effects of hydrogen production from fallen leaves

Factor	Economic considerations	Environmental considerations	Reference
Capital expenditure (CAPEX)	Initial investment for infrastructure setup (equipment, facilities)	Greenhouse gas emissions reduction potential	64
Feedstock cost	Availability and cost of dead leaves	Water consumption during biomass processing	65
Operating costs	Labor, maintenance, energy, raw materials	Land use impact (balancing food and energy crops)	66
Technology-specific costs	Varies by production method (*e.g.*, photo fermentation, dark fermentation)	Sustainable biomass sourcing to avoid deforestation. Life Cycle Assessment (LCA) for overall impact	67

programs that can be used to support collaborative projects. Collaborating with non-profit organizations and non-governmental organizations (NGOs) can provide additional funding and support. These organizations often have missions aligned with environmental sustainability and may offer grants, resources, and advocacy to promote hydrogen production from renewable sources. They can also help raise public awareness and support for the project, which can be beneficial in securing additional funding and partnerships. Public-private partnerships (PPPs) can combine the strengths of both sectors to achieve common goals. In the context of hydrogen production, PPPs can leverage public funding and regulatory support with private-sector innovation and efficiency. These partnerships can help share the risks and rewards of developing new infrastructure, making it more attractive for private investors. Engaging the community through crowdfunding platforms or community investment schemes can provide additional funding and build local support for the project. This approach can also raise awareness about the benefits of hydrogen production from fallen leaves and encourage community involvement in sustainable energy initiatives. By leveraging these funding opportunities and partnerships, the initial infrastructure costs for hydrogen production from fallen leaves can be offset, making the transition to sustainable hydrogen production more economically viable. This approach not only enhances the financial feasibility of the project but also fosters collaboration and innovation across different sectors.

More research is needed to develop effective pre-treatment methods that can standardize the quality of fallen leaves as a feedstock, including understanding the chemical composition of different types of leaves and how they affect hydrogen yield. Identifying the optimal conditions for pyrolysis and fermentation processes is crucial, involving extensive experimental studies and advanced modeling techniques to determine the best operational parameters. There is also a need for the discovery and development of cost-effective and durable catalysts that can enhance hydrogen yield, with a focus on the regeneration and recycling of these catalysts to improve sustainability. Scaling up laboratory-scale processes to industrial levels presents significant challenges, making pilot-scale studies essential to identify and address these issues, and modular reactor designs can facilitate this transition.[69] Detailed economic evaluations, including CAPEX and OPEX, are necessary to understand the financial viability of hydrogen production from fallen leaves, and the impact of government incentives and subsidies should also be explored. Comprehensive life cycle assessments (LCA) comparing hydrogen production from fallen leaves with traditional methods are needed to understand the environmental benefits and trade-offs. The variability in the chemical composition of fallen leaves can affect the consistency and efficiency of hydrogen production processes, making it challenging to standardize the feedstock. Processes like pyrolysis are energy-intensive, impacting the overall energy efficiency and economic viability of hydrogen production from fallen leaves. Managing by-products such as biochar and liquid residues can be challenging, especially in terms of disposal or finding valuable applications. Navigating regulatory requirements and achieving market acceptance for hydrogen produced from biomass can be complex and time-consuming. By integrating various studies and findings, the manuscript provides a comprehensive overview of the current state of hydrogen production from fallen leaves, summarizing the latest research on feedstock variability, process optimization, catalyst development, and economic and environmental impacts. The manuscript adds to the literature by highlighting the potential of using mixed biomass feedstocks, such as the co-fermentation of sewage sludge and fallen leaves, to enhance hydrogen production. It also discusses the integration of biomass gasification with waste management systems, providing practical examples and lessons learned from real-world projects. The manuscript outlines specific questions, recommendations, and future research directions, offering a roadmap for advancing the field. This includes exploring the integration of hydrogen production with renewable energy sources, researching value-added applications for by-products, and studying the feasibility of community-based projects. By addressing these aspects, the manuscript not only integrates existing material but also contributes new insights and directions for future research, making it a valuable addition to the literature on renewable energy and hydrogen production from biomass.[70]

The key takeaways for each section on hydrogen production from fallen leaves highlight several important points. For feedstock variability, the chemical composition of fallen leaves varies by tree species, season, and location, which affects hydrogen yield and process efficiency. Effective pre-treatment methods like drying, grinding, and homogenizing can help standardize feedstock quality for consistent hydrogen production. In process optimization, identifying the optimal conditions (temperature, pressure, residence time) is crucial for maximizing hydrogen yield in pyrolysis and fermentation processes, and different catalysts can significantly influence the efficiency and yield of hydrogen production from fallen leaves. Regarding economic feasibility, detailed cost components (CAPEX and OPEX) for setting up and operating hydrogen production facilities using fallen leaves are essential for economic analysis, and government incentives and subsidies can significantly enhance the economic viability of hydrogen production from biomass. In terms of environmental impact, comparing the life cycle environmental impacts of hydrogen production from fallen leaves with traditional methods is crucial for understanding sustainability, and integrating hydrogen production with existing waste management systems can reduce the overall carbon footprint and enhance environmental benefits.[46] Recommendations include implementing standardized pre-treatment processes and conducting comprehensive studies on the chemical composition of fallen leaves, investing in advanced process control systems, and utilizing machine learning algorithms to optimize process parameters. Future research directions should explore the integration of hydrogen production from fallen leaves with renewable energy sources to improve energy efficiency and reduce costs, research value-added applications for by-products like biochar, develop methods to treat and utilize liquid residues and study the feasibility and benefits of community-based hydrogen production projects while engaging with local communities to foster support and participation. These takeaways provide a concise summary of the critical points discussed in each section, highlighting the potential and challenges of hydrogen production from fallen leaves.[59]

The UN's Sustainable Development Goals (SDGs) highlight the potential of using fallen leaves for hydrogen production. Energy Progress Report 2024 tracks global progress toward SDG 7, which aims to ensure reliable, affordable, sustainable, and modern energy for all. Despite improvements in energy access, efficiency, and renewable adoption, progress is falling short of SDG 7 targets by 2030. Expanding energy access, scaling up renewables, enhancing energy efficiency, and increasing financial flows to developing countries for clean energy projects are crucial. Hydrogen, a promising clean energy source, plays a vital role in decarbonization and achieving net-zero emissions by 2050. Techniques for generating hydrogen are essential for a clean environment and sustainable energy solutions. Biochemical hydrogen production, using waste organic matter instead of fossil fuels, produces clean energy and contributes to efficient waste management. Additionally, the policy toolkit emphasizes green hydrogen's potential as a catalyst for environmental sustainability, economic growth, and social progress in developing countries.[71]

7. Conclusion

Hydrogen emerges as a promising sustainable energy solution characterized by its clean-burning properties and versatility. Current hydrogen production techniques include electrolysis and steam methane reforming, with the former showing promise for renewable hydrogen production but facing persistent challenges. Transitioning to renewable hydrogen holds significant promise for mitigating greenhouse gas emissions, yet requires substantial investment in research and infrastructure. Despite environmental concerns, steam methane reforming remains dominant in hydrogen production, highlighting the ongoing need to address cost-effectiveness and scalability in renewable hydrogen technologies.

Efforts should concentrate on enhancing electrolysis efficiency, exploring alternative feedstocks, and developing robust storage and transportation solutions critical for widespread hydrogen adoption. This review emphasizes hydrogen's crucial role in sustainable energy solutions, stressing the necessity for collaborative efforts across sectors to facilitate its integration. Just as fallen leaves enrich the soil, hydrogen has the potential to transform our energy landscape, but achieving this vision demands concerted action and steadfast commitment.

Data availability

All the actual data are presented in the manuscript.

Conflicts of interest

Authors declare no competing interests.

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