Harnessing the potential of bio-resources to produce

LOW CARBON
BIO-HYDROGEN


H2
H2

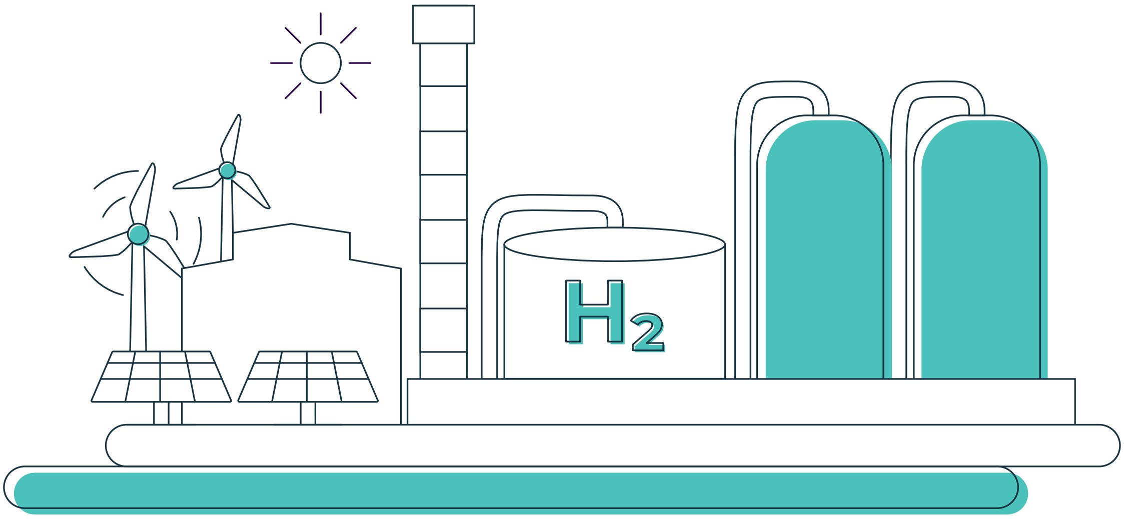
CONTENTS

EXECUTIVE SUMMARY

Hydrogen is the cleanest energy form that yields highest energy per gram of any known fuel. On combustion it produces only water. H_2 can be produced through different pathways from various sources. Current hydrogen demand (> 95%) is fulfilled by producing hydrogen from fossil-based resources that is associated with release of Green House Gas (GHG). Though H_2 as an energy form has great potential to reduce GHG, its production from fossil-based resources is not clean. In this context biohydrogen produced from alternate renewable resources has significant environmental benefits as this process can valorise organic waste, biomass (lignocellulose biomass, algae biomass) and organic acids through fermentation route and from water through bio-photolysis route.

Among all bioprocesses, dark fermentation pathway is widely explored globally to produce biohydrogen as this process can valorise waste. Current major challenge of this process is high process cost that is attributed to the conversion of 60% of feed to metabolites such as, short chain organic acids (acetic acid, butyric acid, propionic acid, lactic acid), ethanol. In order to reduce the process cost and to make it sustainable, it is essential to use low-cost feed and to recover the value-added metabolites or to integrate for production of H_2, PHA, biomethane, lipid, in a biorefinery approach. This can aid in making this process zero waste and circular.

In addition, when operating on real-time data of the production environment, statistical and AI/ML-based methods may be used to simulate the yield and study the variables impacting biohydrogen generation.



Key insights

The worldwide market for hydrogen produced from electrolysis was far larger than the market for biohydrogen as per 2021. Biohydrogen is typically produced through fermentation of organic materials such as agricultural waste or algae, while electrolysis hydrogen is produced through the electrolysis of water using electricity generated from renewable energy sources.

According to a report by Allied Market Research published in 2020, the global biohydrogen market size was valued at $64.2 million in 2019 and was projected to reach $99.6 million by 2027, growing at a CAGR of 5.6% from 2020 to 2027. In contrast, the global electrolysis hydrogen market size was valued at $0.87 billion in 2019 and was projected to reach $28.58 billion by 2027, growing at a CAGR of 51.2% from 2020 to 2027, according to a report by Markets and Markets published in 2020.

It is important to note that both industries are anticipated to expand significantly over the next several years due to a variety of causes, including rising clean energy demand, backing from the government for hydrogen technologies, and improvements in infrastructure and technology.

In 2020, based on production method, fermentation acquired the most market share in the Global Bio Hydrogen market

The hydrogen market is experiencing up to 10%[1] growth year on year and is forecasted to reach over $191.80 Bn in 2024

Producing biological hydrogen (H_2) generation technologies using eco-friendly resources to assist in fulfilling the country's demand for renewable energy.

Due to its abundance and high sugar content (around 40% cellulose and 30% *hemicellulose*), lignocellulosic biomass is a desirable feedstock to produce hydrogen by dark fermentation.

Although the use of microalgae to produce hydrogen gas from water photolysis has been researched for a long time, there are still numerous obstacles preventing its commercialization.

Most obstacles to commercialization are related to biological regulatory systems that, in anaerobic environments, quench the absorbed light energy, down-regulate linear electron transport, inactivate the H_2 producing enzyme, and compete for electrons with the hydrogenase.

INTRODUCTION

Energy is a vital input for socioeconomic development of a nation. Current energy production technologies are mostly relying on fossil-based resources that are associated with substantial Green House Gas (GHG) emissions along with depletion of energy resources. In this regard, renewable energy production from alternate resources is gaining global attention owing to their potential for GHG emission reductions. With an aim to reduce carbon intensity and to make India energy self-reliant, the Prime Minister of India has declared the "Panchamritra" strategy at Cop26[1] . This strategy aims at meeting 50% of its energy demand from renewables by 2030 and to achieve net zero target by 2070.

Among various renewable fuel forms, green hydrogen is gaining global attention as the most promising and cleanest fuel form, in view of its non-reliance on petroleum resources, high efficiency for conversion to power, highest gravimetric energy density, its ease of transportation and its carbon neutral nature. Also, hydrogen on combustion releases clean water

Green hydrogen can be produced through different pathways from various renewable resources such as from water through electrolysis and bio-photolysis route, and from biomass through biological pathway and thermochemical pathway. Hydrogen produced from biomass through gasification pathway, from biomass, carbohydrate-based feed, and water through biological pathway is termed as 'Biohydrogen'.

The Global Bio Hydrogen Market is projected to grow at a CAGR of 6%[2] in the forecast period of 2021-26, reveals MarkNtel Advisors in their recent research report.

[1] *IEA at COP26: The role of hydrogen in the transition to net zero*

[2] *Global Bio Hydrogen Market Analysis, 2021*

Key drivers

DEMAND OF FCEV'S

a. It is anticipated that the demand for Fuel Cell Electric Vehicles (FCEVs), such as buses, trucks, passenger cars, and heavy vehicles, among others, would have a beneficial impact on the global bio hydrogen market.

b. By 2030, the market for fuel cell electric vehicles is expected to be worth around $35.60 billion.

FOCUS ON USING CLEAN ENERGY

a. Several countries are working to adopt alternatives like bio hydrogen and lessen their reliance on fossil fuels.

b. The annual demand for hydrogen would reach 200 Mt in 2030 and 530 Mt in 2050, according to the global hydrogen review 2021.

INCREASE USE OF DARK FERMENTATION

a. Dark fermentation is quite straightforward, and productivity is not limited by the availability of light.

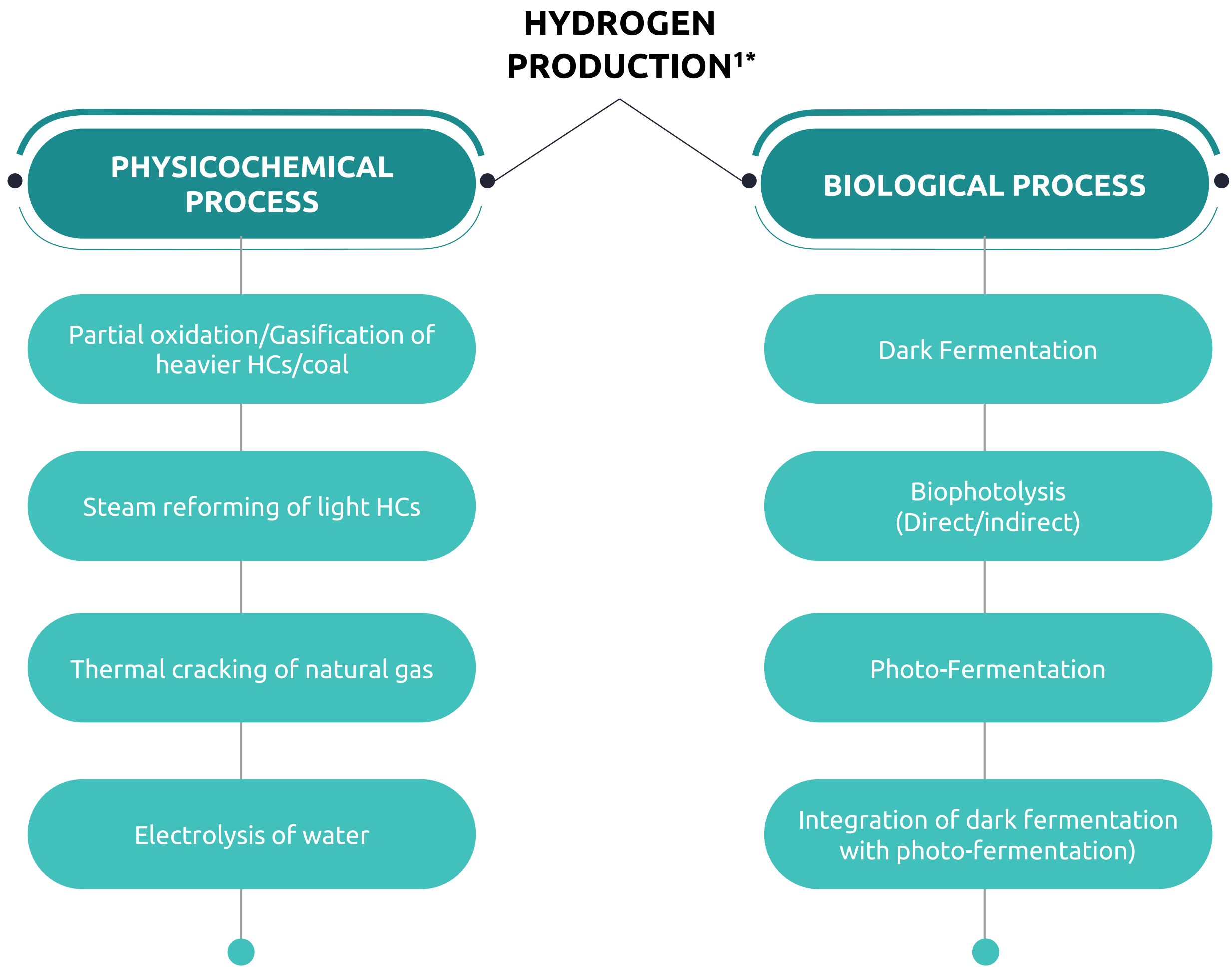
b. Since organic wastes are generally abundant, renewable, affordable, and highly biodegradable, using them as feedstocks in the manufacture of dark fermentative biohydrogen may be cost-competitive.

REDUCTION IN FOOD WASTE

a. Around the world, 1.3 billion tonnes of food are lost each year and end up in landfills.

b. Given that food waste (FW) contains a lot of carbohydrates, which are necessary for the generation of hydrogen, it can be transformed into hydrogen.

Biohydrogen production through different biological pathways



Physico-chemical process:

•High energy intensive.

•Emits green house gas

Biological Processes:

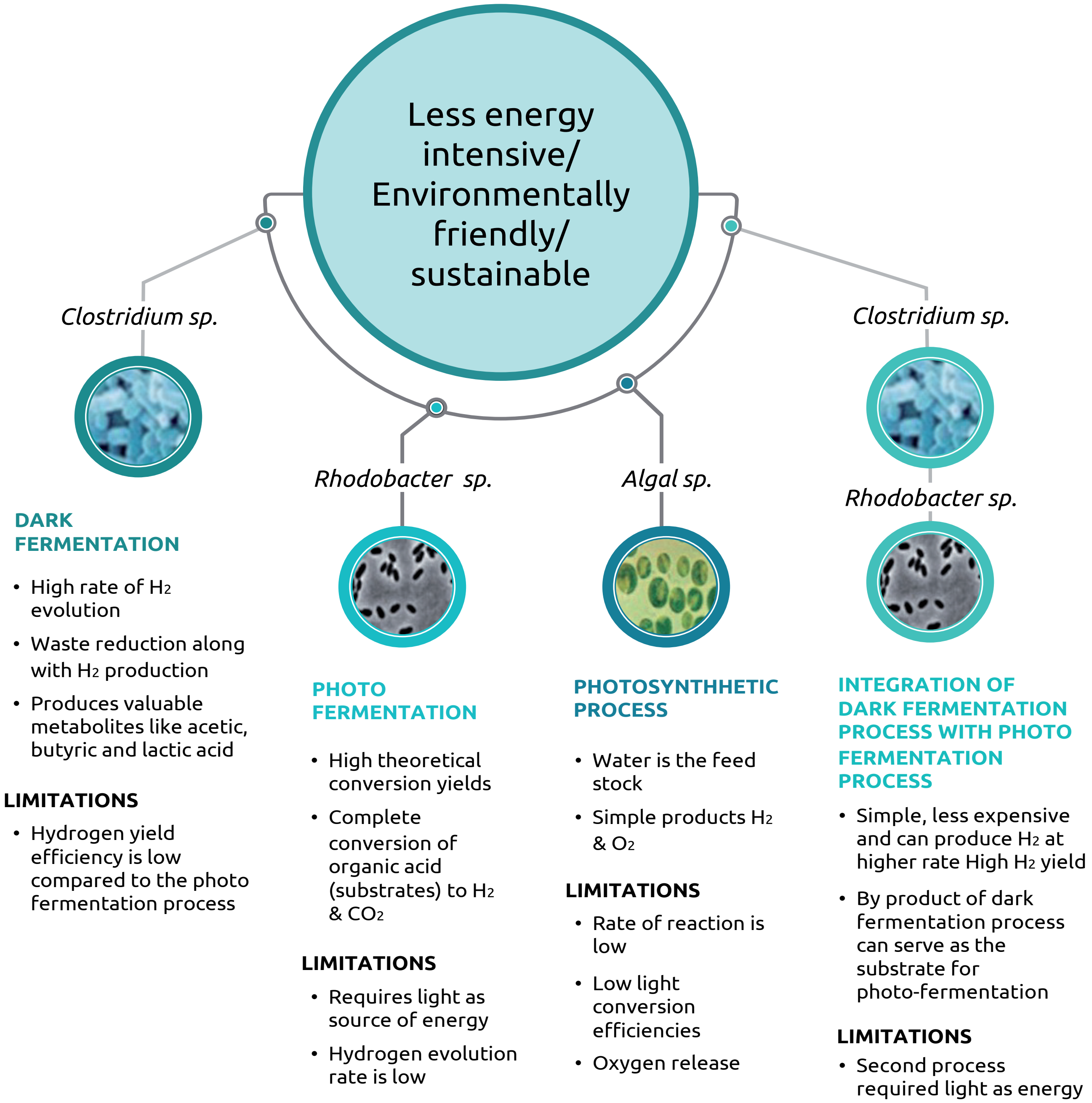
- Less energy intensive and can be operated at ambient temp. and pressure.
- Environmental friendly

[1] *Springer book- Prospects of Alternative transportation Fuels pp 23-28, 2018*

On the contrary, hydrogen production processes through biological route are less energy intensive, can be generated from renewable sources from organic wastes and thus are sustainable. Biological hydrogen production processes have the potential to help in waste management through simultaneous energy recovery and promote circular bioeconomy.

Biologically hydrogen can be produced by few of the unique microbes/ algae though four distinct approaches.

- **Bio-photolysis** of water using select algae/cyanobacteria,
- Photodecomposition of organic compounds through **photo fermentation** pathway mediated by select photosynthetic bacteria as host.
- Hydrogen production through **dark fermentation** pathway through use of select anaerobic bacteria as host
- **Hybrid** biological hydrogen production through integration of dark fermentation process with photo fermentation process.



HYDROGEN PRODUCTION BY DIFFERENT UNIQUE MICROBES THROUGH DIFFERENT PATHWAYS[1*]

[1] *Springer book- Prospects of Alternative transportation Fuels pp 23-28, 2018*

Each of these pathways have several advantages as well as challenges

Dark fermentation pathway does not require light as energy input, can make use of carbohydrate-based waste/ industry spent matter as feed to produce hydrogen and rate of H_2 production through this pathway is high and thus widely explored globally. Molasses, 2nd generation agriculture residue biomass and 3rd generation algae biomass including carbohydrate based spent matter from industries are being explored to recover clean hydrogen. However, H_2 yield through this rout is low as major fraction of input feed get converted to value intermediate metabolites, short chain organic acids, and ethanol, and to make this process economically viable, it is essential to recover these high value bio commodities or to use these molecules as feed to recover hydrogen through integration with photo fermentation route.

Photo-fermentation pathway got advantage in terms of high H_2 yield efficiency and purity of the biogas that contains 96% H_2 and compatible to use directly in the Fuel Cell to generate power. However, this process requires light as energy source and rate H_2 production through this route is less compared to that of dark fermentation pathway. Scaling up of this process requires large scale anaerobic photo bioreactor, which is yet to be demonstrated at higher scale.

Bio-photolysis route can use water as feed to produce clean H_2 through use of inexpensive select algae, cyanobacteria as biocatalyst unlike water electrolysis route that needs expensive catalyst to produce H_2 from water. However, this process release O_2 during H_2 production which inhibits the Hydrogenase enzyme that catalyses water elecro9lysis to produce H_2 and thus needs separation.

Integration of dark fermentation process with photo fermentation process in the second stage can help in enhancing the overall H_2 recovery efficiency from input feed and make the process viable. However, the H_2 production through 2nd stage photo fermentation route is slow.

PRODUCTION PROCESS	CHALLENGE DESCRIPTION	SOLUTIONS
DARK FERMENTATION	▪ The design and scaling-up of hydrogen fermentation systems is largelya trial-and-error process requiring much time, cost, and effort ▪ The dominant cost element in fermentative hydrogen production is the substrate.	▪ Process modelling and simulation using Computational Fluid Dynamics (CFD) tools provides an analytical framework that can help identify and overcome scaleup issues before real operation ▪ biohydrogen production with the use of cheaper lignocellulosic substrates will be crucially important for hydrogen
PHOTO FERMENTATION	▪ Photo fermentative biohydrogen production would require larger reactor size than dark fermentative hydrogen production for the same hydrogen production rate ▪ It is a complicated system affected by pre-treatment method, raw material, configuration of the photobioreactor, light distribution and density, and light-heat-mass transfer properties	▪ More amount of biohydrogen could be produced by mutagenesis and genetic engineering techniques ▪ To optimize production and commercialization, more efforts are needed for in-depth understanding, especially regulation mechanism of photosynthetic hydrogen production.
BIO PHOTOLYSIS	▪ Use at subcellular particles and proteins, although a Useful laboratory technique for study of basic mechanisms, is not an economically feasible approach to practical bio photolysis	▪ Large industrial processes rely on enzyme technology; as it would be required for practical application in bio photolysis ▪ Attainable photosynthetic efficiencies long half-life of the system, stoichiometric ratios of hydrogen to water produced, and facile operations and control are minimum requirement
MEC – MICROBIAL ELECTROLYSIS CELL	▪ The production efficiency decreases as the volume increases due to increased application of electrodes ▪ The durability of the electrode material is a challenge as they are fragile when expanded, causing performance deterioration and maintenance difficulty. ▪ It faces challenges in large-scale applications due to its design, electrodes, membrane cost, etc	▪ Maintaining proportionate hydrogen production with an increase in size is needed. ▪ The difficulties of MEC could be solved by price and performance innovations for key components.

Source : Dark Fermentation; Photo; BIO; MEC

MILESTONES

The Department of Biotechnology, Hindustan Petroleum Corporation Limited (HPCL), Center for High Technology (CHT), Ministry of Petroleum and Natural Gas (MoPNG), and Ministry of New and Renewable Energy (MNRE) provided financial support to TERI to conduct extensive research on fermentative hydrogen production in order to achieve the goal of sustainability. The successful development of a pilot 1000-liter scale fermentation process for hydrogen production from sugar cane blackstrap molasses was made possible by in-depth research explorations conducted by TERI with the help of the institute's current state-of-the-art large scale fermentation facilities.

Considering concerns about food security, further research investigations in this area have concentrated on the synthesis of hydrogen from lignocellulosic/ woody biomass. Lignocellulosic biomass is most prevalent in nature and can be used in a variety of ways as a non-feed competitive feedstock for the manufacture of clean fuels. It is present in agricultural leftovers, grasses, hardwoods, and softwoods. These biomass samples, however, are primarily made of cellulose and hemicellulose polymers (polymers of glucose, a C6 sugar, and xylose, a C5 sugar). Most microorganisms use glucose efficiently. However, the use of xylose, a C5 sugar, is the key. Only bacteria capable of using C5 and C6 sugars may utilise lignocellulosic biomass as a feedstock for the creation of biofuels.

To close the gaps in the transition and get this technology to demonstration/ pre-commercial size, more research activities are now being conducted in this area. The creation of value-added products using the process' discarded effluent is being explored as a biorefinery idea in order to minimise the process' total cost, which is currently one of the main issues. The process's costs will eventually be significantly reduced when this technology matures.

https://www.teriin.org/blog/producing-hydrogen-biological-way
https://www.teriin.org/article/producing-hydrogen-agriculture-waste-microbial-way

Biohydrogen production through dark fermentation route: Potential for waste valorisation coupled with H_2 and volatile fatty acids:

European and North American countries are the leaders in the market share of the global biohydrogen market production as well as consumption. Asian region market is anticipated to show the highest CAGR with the continuous increase in the government funding for research and developments in the field of Biohydrogen

Biohydrogen though widely explored globally, it is yet to be commercialized. Major challenge is the high process cost that is associated with high feed cost. To address this, low cost biowaste/ organic rich wastewater/ spent effluent can be used as feed for biohydrogen production. To enhance biohydrogen yield it is desirable to use select high H_2 yielding microbe(s). Valorisation of organic rich wastes such as food waste, agricultural waste, industrial waste, agriculture waste, coupled with H_2 production, offers promising approach in the context of sustainable management of environment and process cost reduction.

Municipal/Domestic waste as feed:

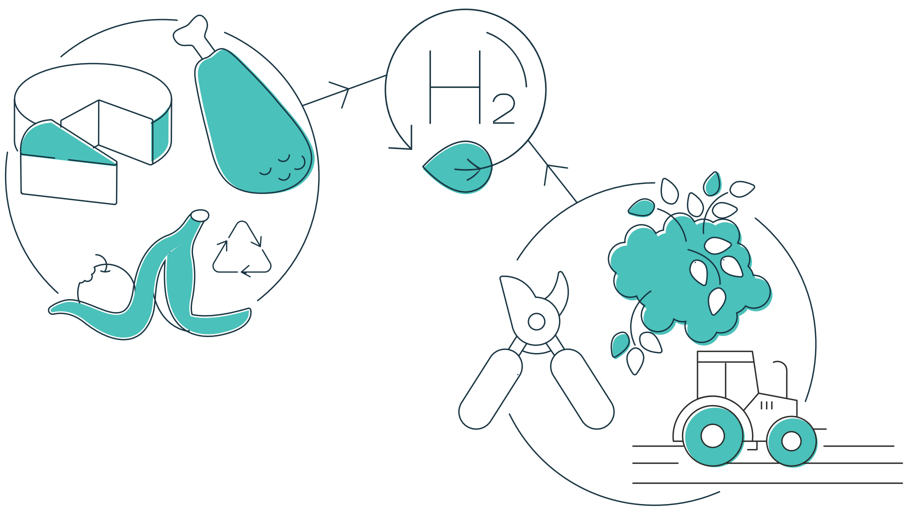
Use of domestic waste as inexpensive feed for biohydrogen production can aid in reducing the production cost along with treatment of these hazardous waste. Municipal solid waste generation has increased substantially, owing to urbanization, population growth and economic growth and it projected to increase by **70% to 3.4 billion metric tons.** These wastes are rich in organics and require adequate treatment prior to disposal. Less than **20%** of this waste is recycled each year and rest is dumped into the open environment, landfill sites. These wastes after appropriate pre-treatment can serve as inexpensive feed for biohydrogen production and value-added organic acid, acetic acid, butyric acid and ethanol production, in a waste bio refinery approach.

Food waste as feed:

According to FAO's report, around **14%** of world's food is lost (valued USD 400 billion per year) during harvesting and further **17%** food is being wasted by consumers in households. Food loss and waste contribute to 8-10% worldwide GHG emissions. Food waste is rich in carbohydrates/organics and can be used as good feed source for biohydrogen production and volatile fatty acid production or biomethane production in an integrated manner to make this process circular, zero waste. Starch based food waste needs mild pre-treatment for H_2 production yield enhancement from this feed. This can contribute towards reducing the H_2 production cost and to valorise food waste. Select starch utilizing microbes can be used to produce H_2 from starch-based food waste directly.

Agriculture waste as feed:

Agriculture wastes are generated from various sources, agriculture crop residue, livestock and agro industries. These wastes are complex and composed of cellulose, *hemicellulose* and *lignin*. Major issue is sustainable management of these wastes, generally burned or buried, leading to air and water pollution and global warming. 60-70% of these agriculture wastes is carbohydrate and have great potential to be used as feed for biohydrogen production through dark fermentation route. However, these wastes need appropriate treatment to recover fermentable sugar fractions that can be used as feed for H_2 production. To make this process circular and zero waste, H_2 production from these wastes can be integrated with volatile fatty acid production and lignin-based bio commodity production.



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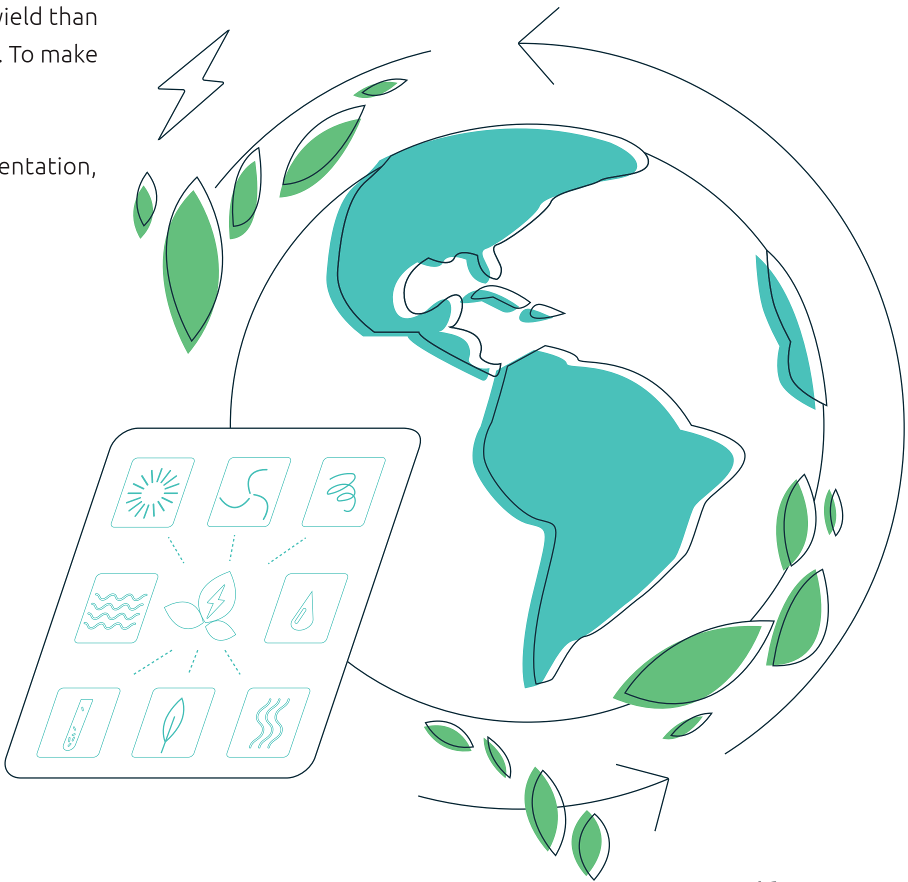
Role of engineering and technology to

OVERCOME PROBLEMS

While the commercial viability of industrial scale biohydrogen production can be debated, there is an increasing role for modern technologies in the evaluation of the most optimum production pathway, controlling the production environment and estimation of the overall yield.

To cite examples, the production efficiency through the dark fermentation process can be increased using sensors which determine accurate pH level of the environment, necessary to maintain the microbial activity and metabolic pathway for biowaste degradation. Statistical and AI/ ML-based tools can be deployed for mathematical modelling to analyze the factors affecting biohydrogen production and predict the yield, acting on real-time measurements of the environmental conditions of production.

Scientific studies are being done for developing lab-engineered microbes, with enhanced metabolic activity, to produce much higher biohydrogen yield than what can be achieved under normal conditions. To make biohydrogen production viable, some labs are experimenting with the design of an advanced bioreactor, equipped with sensors and instrumentation, to measure the ambient conditions, control the microbial decomposition of wastes, and to ensure a steady and continuous production of biohydrogen. There is a scope for deploying machine learning capabilities for biowaste profiling and predicting microbial activity linked to biohydrogen production. Also, biohydrogen facilities require energy for production. Clean, renewable energy including that from biomass can be gainfully utilized, while promoting sustainability in biohydrogen production.

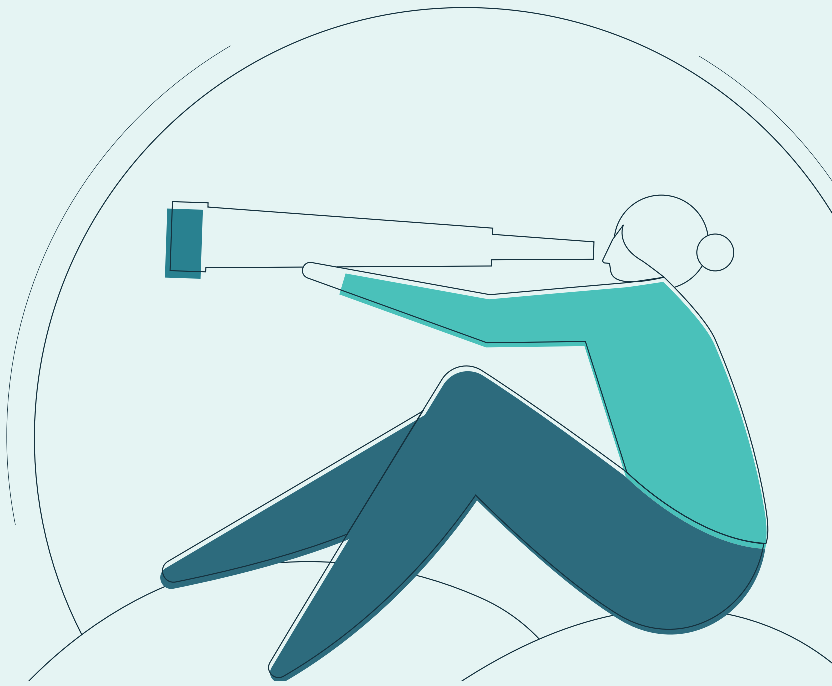


CONCLUSION

Biohydrogen production from low-cost waste is a sustainable approach that has dual benefits for waste treatment along with H_2 and volatile fatty acid production. This can contribute immensely towards the reduction of H_2 production cost and for sustainable environment management in a circular bioeconomy framework. Most obstacles to commercialization are related to biological regulatory systems that, in anaerobic environments, quench the absorbed light energy, down-regulate linear electron transport, inactivate the H_2 producing enzyme, and compete for electrons with the hydrogenase.

The conversion rate of absorbed photons to H_2 is substantially less than its projected potential of 12–13%. However, there is a lot of research being done to get around these barriers, either by understanding and manipulating the metabolic and enzyme-level intracellular regulatory mechanisms, or by developing biological systems that can continue to produce H_2 even when the solar conversion is only between 12 and 13%.

Though the financial viability of large-scale biohydrogen production is debatable, current technologies are playing a larger and larger role in the analysis of the best production pathway, management of the production environment, and assessment of the total yield. When operating on real-time observations of the production environment's environmental conditions, statistical and AI/ML-based techniques may be used to model mathematically assess the factors impacting biohydrogen production and estimate the output.



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TERI'S DOMAIN EXPERTISE

TERI's energy program: 1. Analyses regulatory needs of energy-based industries like coal, oil, natural gas, and electricity , 2. Provides RE - based technological solutions for diverse user-groups within industrial, commercial and residential sectors, 3. Undertakes energy auditing of, and supports adoption of energy – efficient technologies among heavy industries and MSMEs

Given the rising population levels, and with it the pressure on varied resources for developmental needs, TERI conducts feasibility studies for, and supports strengthening the institutional capacity of urban local bodies (ULBs) for better management of municipal solid waste

TERI is working toward the commercialization, and large-scale uptake of its patented technology 'TADOX' (TERI's Advanced Oxidation Process), and Ceramic Membrane for affordable treatment of wastewater in industrial complexes

TERI conducts ecological assessments of biodiverse regions, provides valuation of ecosystem services, besides promoting biodiversity conservation, especially by leveraging innovative financial mechanisms

The Sustainable Agriculture program develops plant and microbe - derived products, using nano biotechnology to reduce utilization of chemical fertilizers, while simultaneously improving crop yields.

The TERI – Deakin Nano Biotechnology Centre aims to take up the global agriculture space through technology interventions in sustainable agriculture by employing multidisciplinary approaches, tools and methodologies.

Established with the objective of promoting sustainable development, TERI, in alignment with, and for the implementation of this mission, has developed several products, and provides services to public and private stakeholders. These offerings range from carrying out on-field assessments and audits, to enhancing institutional capacity of implementing agencies, to providing policy analysis.

Some of the programs and projects TERI is working on are provided below:

The Environmental and Industrial Biotechnology program is engaged in developing sustainable solutions like bioremediation, microbial oil enhanced recovery and biologically enhanced methane production. Work under this program has successfully yielded the 'oil zapper', a product, which helps clean up oil-spills and oil contaminated sites. Additionally, the program also produces biopolymer as a drilling mud for use by oil companies, whose commercialization is taken care by ONGC TERI Biotech Ltd (a joint venture of Oil and Natural Gas Corporation Limited and TERI).

The Climate and Air programme is the dedicated wing of TERI for assessment and modelling studies on climate change. The climate team uses varied modelling tools to provide scenario analysis and risk planning services to industries, besides supporting state agencies on their climate action policies. Further, the climate team at TERI: i) provides inputs to international climate negotiations, ii) analyzes domestic and international climate finance markets, and iii) assists public and private planners in implementing climate mitigation and adaptation actions.

A focus area TERI is keen to promote sustainability in is the shipping industry. The Green Shipping programme undertakes sustainability assessments of varied products, especially, focusing on resource governance and promoting circular economy. Further, the programme is exploring the development of technologies for the production of green chemicals, and advanced biofuels – a key component of securing India's energy needs.

TERI is helping embed sustainability across key infrastructural sectors of buildings, transportation and urban governance, and water. The guideline on sustainability in built infrastructure, 'GRIHA', developed by TERI, is the national rating system for green buildings, officially adopted by the Ministry of New and Renewable Energy (MNRE).

In support of creating liveable and smart cities, the urban and transportation division engages in research and policy analysis, and provides advisory and capacity building services to Urban Local Bodies (ULBs).

TERI helps industries manage their water footprint by offering auditing services and integrated water resources management. Additionally, the division engages in glacier vulnerability assessments, especially integral for the preservation of the Himalayan ecology.

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ANNEXURE

More information on select TERI solutions can be found by scanning the following QR codes -

Oil Zapper

TADOX

Ceramic Membrane for Treating Industrial Wastewater

Find Capgemini's reports and POVs on scanning the QR codes below:

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About
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The Energy and Resources Institute (TERI) has almost 50 years of experience in climate change research and policy practice across various geographies of the developing world, particularly in Asia. Research activities at TERI have focused on understanding, analyzing and promoting awareness related to local and global environmental issues with a multi sector overview. TERI works in close collaboration with various stakeholders including national and international governments, bilateral and multilateral agencies, civil society, and sector experts. The institute provides both technological as well as policy advice, bringing together not only learning from different regions and user groups with varied socio-economic and cultural backgrounds, but also state of the art methods and technological rigor to enable more effective national and global policy decisions.

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