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Hydrogen from Dairy Waste: A Clean Energy Solution from the Dairy Sector

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Abstract

Hydrogen has emerged as a pivotal clean fuel for decarbonizing future energy systems due to its high energy density and zero-carbon emissions at the point of use. Currently, hydrogen production is dominated by fossil-fuel-based processes such as steam methane reforming, which are carbon-intensive. In contrast, biohydrogen derived from organic waste streams represents a renewable and environmentally friendly alternative. The dairy industry, a key agro-industrial sector globally, generates vast quantities of organic-rich waste such as cheese whey, skim milk and effluents, which often remain underutilized or improperly managed. These substrates are particularly suitable for biological hydrogen production due to their high biodegradable content. This article explores various hydrogen production technologies, with a focus on biological processes such as dark fermentation, photo-fermentation and microbial electrolysis cells (MECs), including recent advances like lactate-driven dark fermentation (LD-DF). The work also discusses the advantages of using dairy waste, associated challenges and future directions for research, especially in the context of India's growing dairy sector and clean energy initiatives.

Keywords: Dairy Processing, Waste, Hydrogen, Biological Process

Introduction: The Hydrogen Revolution

Hydrogen is increasingly being recognized as a cornerstone of the clean energy transition due to its ability to store large amounts of energy and its versatility in sectors ranging from transportation and power generation to industrial applications such as steelmaking and ammonia production. However, approximately 95% of global hydrogen is still derived from fossil fuel sources, primarily through steam methane reforming (SMR), which emits significant quantities of CO_2 and undermines the sustainability of hydrogen as a clean fuel (IEA, 2023).

To address this issue, attention has turned to biohydrogen—hydrogen produced through biological or thermochemical conversion of renewable biomass or organic waste. Among the various types of biomasses, dairy industry residues stand out due to their continuous availability, high organic load and susceptibility to microbial degradation. India, being the world's largest milk producer, generates over 150 million tonnes of dairy waste annually (NDDB, 2022). Transforming this waste into hydrogen represents a promising strategy for both clean energy generation and sustainable waste management.

Hydrogen Production Technologies: An Overview

Hydrogen can be generated through several technological pathways that differ in their feedstocks, environmental impacts and scalability. Grey hydrogen, the most common form, is produced by reforming natural gas but results in high CO_2 emissions. Blue hydrogen follows the same process but integrates carbon capture and storage (CCS) systems to mitigate emissions, albeit at a higher cost. Green hydrogen, considered the cleanest form, is produced via electrolysis of water using electricity from renewable sources such as solar or wind, although it remains energy-intensive and capital-heavy.

In contrast, biohydrogen is produced from organic substrates through biological or thermochemical processes. These include anaerobic digestion, dark fermentation, photo fermentation, microbial electrolysis, gasification and pyrolysis. As it utilizes waste feedstocks, biohydrogen offers the dual benefit of clean energy production and organic waste remediation, making it particularly attractive for circular bioeconomy models.

Table 1. Overview of Hydrogen Production Technologies

Technology	Description	Characteristics
Grey Hydrogen	Produced from natural gas via steam methane reforming (SMR).	Economical but emits large amounts of CO_2.
Blue Hydrogen	Similar to grey hydrogen but includes carbon capture and storage (CCS).	Cleaner than grey hydrogen but more expensive.
Green Hydrogen	Produced by electrolyzing water using renewable electricity.	Emission-free but energy-intensive and costly.
Biohydrogen	Derived from organic waste biomass using biological or thermochemical processes.	Sustainable, scalable and decentralized.
Turquoise Hydrogen	Produced via methane pyrolysis, generating solid carbon instead of CO_2.	Technology not yet commercially viable.

Dairy Waste: A High-Potential Substrate for Biohydrogen

The dairy industry produces a wide array of waste materials, including cheese whey, product residues, cleaning effluents and sludge from wastewater treatment. These wastes are characterized by high levels of biochemical oxygen demand (BOD) and chemical oxygen demand (COD), indicating a rich supply of fermentable organic matter. For instance, cheese whey is rich in lactose and proteins that serve as excellent substrates for hydrogen-producing microorganisms.

If left untreated, these effluents contribute to environmental degradation through eutrophication and methane emissions. However, their high biodegradability and availability make dairy wastes ideal candidates for biohydrogen production. According to Choudhary *et al.* (2023), dairy waste not only provides essential nutrients for microbial metabolism but also supports hydrogen production through various biological processes when appropriately conditioned.

Biological Hydrogen Production from Dairy Waste

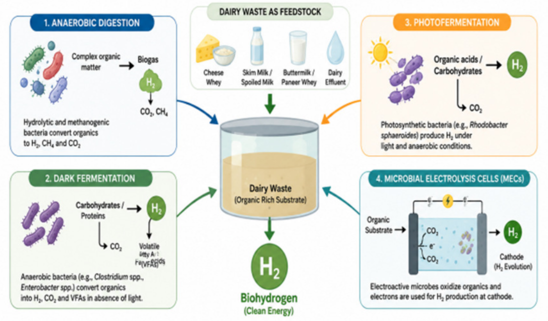

Fig. 1. Different biological hydrogen production from dairy waste

a. Dark Fermentation

Dark fermentation is a microbial process where anaerobic bacteria such as *Clostridium spp.* and *Enterobacter spp.* convert sugars and proteins in dairy waste into hydrogen, CO_2 and volatile fatty acids (VFAs) in the absence of light. It is one of the most extensively studied and technically viable biohydrogen pathways due to its simplicity, continuous operation and compatibility with various waste substrates.

Ghimire *et al.* (2015) reported a maximum hydrogen yield of 2.3 mol H_2 per mol of hexose using optimized conditions with dairy whey, although practical yields are often lower due to microbial inhibition, substrate variation and by-product accumulation. The primary limitation of dark fermentation lies in the accumulation of VFAs such as acetate and butyrate, which can inhibit microbial activity and reduce process stability.

b. Lactate-Driven Dark Fermentation (LD-DF)

A recent advancement in the field is lactate-driven dark fermentation (LD-DF), which utilizes pre-fermented dairy waste rich in lactate to enhance hydrogen production. In this process, lactic acid bacteria (LAB), such as *Lactobacillus spp.*, convert lactose in cheese whey into lactate. Subsequently, hydrogenogenic bacteria like *Clostridium tyrobutyricum* utilize lactate to produce hydrogen and butyrate.

Aranda-Jaramillo *et al.* (2025) demonstrated a significant improvement in hydrogen yield through LD-DF, reporting up to 7.8 L H_2/L/day in a continuous anaerobic stirred tank reactor. The study also revealed that lactate-to-butyrate conversion pathways were critical for maintaining high hydrogen productivity and excessive lactate accumulation led to reduced hydrogen output. This process also mitigated the risk of VFA inhibition by redirecting lactate metabolism toward favourable hydrogen-producing pathways.

c. Photo-fermentation

Photo-fermentation uses photosynthetic purple non-sulphur bacteria, such as *Rhodobacter sphaeroides*, to convert VFAs into hydrogen under light conditions. Although it allows for further conversion of by-products from dark fermentation, the method is sensitive to oxygen, requires light input and is slower than dark fermentation. Nevertheless, when integrated in a two-stage process with DF, photofermentation enhances overall substrate utilization and hydrogen recovery.

d. Microbial Electrolysis Cells (MECs)

MECs represent an advanced bio-electrochemical system where electroactive microbes break down organic matter and transfer electrons to an anode. With a small voltage input, hydrogen is produced at the cathode. Logan and Rabaey (2012) emphasized the potential of MECs in treating high-strength organic wastewater, including dairy effluent, while recovering energy as hydrogen. However, the capital cost of electrodes and complexity of the system remain significant barriers to rural deployment.

e. Thermochemical Pathways for Hydrogen from Dairy Waste

Thermochemical methods such as gasification, pyrolysis and steam reforming of biogas are generally applied in industrial settings where dairy sludge and concentrated wastes are available. Gasification involves heating waste in limited oxygen to produce syngas, which is then separated into hydrogen and other gases. Pyrolysis thermally decomposes organic matter in the absence of oxygen, generating bio-oil, char and gases, the latter of which can be reformed to hydrogen. Additionally, biogas derived from anaerobic digestion of dairy waste can be steam-reformed to produce hydrogen, particularly when methane content is high. These methods are more energy-intensive but well-suited to centralized dairy processing plants that can integrate heat recovery systems.

Benefits of Hydrogen Production from Dairy Waste

Utilizing dairy waste for hydrogen production offers numerous environmental and socioeconomic benefits. Environmentally, it reduces the load of untreated effluents entering water bodies, thereby mitigating eutrophication and methane emissions. From an energy perspective, it transforms a problematic waste stream into a clean and renewable fuel. This not only supports energy self-sufficiency in rural areas but also aligns with sustainable development goals (SDGs), especially SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production). Economically, decentralized hydrogen production through dairy cooperatives can foster rural entrepreneurship, create green jobs and contribute to India's broader clean energy transition under its National Green Hydrogen Mission.

Challenges and Research Gaps

Despite the promising outlook, several technical and economic barriers hinder the commercialization of hydrogen production from dairy waste. One of the most pressing issues is the relatively low hydrogen yield and operational instability of biological processes. Accumulation of VFAs and ammonia from protein degradation inhibits microbial metabolism and necessitates sophisticated control strategies. Furthermore, dairy waste often contains complex substrates requiring costly pre-treatment steps such as enzymatic hydrolysis or alkali treatment.

In rural areas, the adoption of biohydrogen technology is limited by a lack of awareness, insufficient infrastructure and inadequate technical expertise. The high cost of advanced reactors such as MECs and photobioreactors further restricts deployment in decentralized settings. Aranda-Jaramillo *et al.* (2025) also noted that microbial community shifts and accumulation of acetate and lactate were major factors impacting hydrogen yield, highlighting the need for microbial engineering and process optimization.

Future Research Directions

To overcome existing barriers, future research should focus on several key areas. Genetic and metabolic engineering of hydrogen-producing microbes can enhance tolerance to inhibitors and improve substrate utilization efficiency. Integrating co-digestion strategies, such as combining dairy waste with food waste or crop residues, may optimize carbon-to-nitrogen ratios and buffer system imbalances. The development of modular, low-cost bioreactors with automated monitoring systems is critical for expanding deployment in rural areas.

Furthermore, techno-economic modelling must be employed to evaluate the feasibility of various process configurations under different scales. Policy support in the form of capital subsidies, tax incentives and feed-in tariffs will be instrumental in encouraging industry adoption. Integration with national and international clean energy initiatives will be essential to realize the full potential of biohydrogen from dairy waste.

Conclusion

The valorisation of dairy waste for hydrogen production offers a compelling solution to two pressing challenges: clean energy generation and organic waste management. With technological innovations such as lactate-driven dark fermentation and supportive policies under India's Green Hydrogen Mission, the dairy sector has the potential to become an important contributor to a decentralized hydrogen economy. Realizing this vision will require interdisciplinary research, stakeholder collaboration and scalable, cost-effective solutions tailored to the needs of rural and semi-urban dairy systems.

References

Aranda-Jaramillo, B., Arreguín-Espinosa, R., Olvera, A. G., & Méndez-Acosta, H. O. (2025). Continuous hydrogen production via lactate-driven dark fermentation using cheese whey: Cooperative metabolism and microbial dynamics. *Journal of the Taiwan Institute of Chemical Engineers*, *152*, 106307. https://doi.org/10.1016/j.jtice.2025.106307

Ghimire, A., Frunzo, L., Pirozzi, F., Trably, E., Escudié, R., Lens, P. N., & Esposito, G. (2015). A review on dark fermentative biohydrogen production from organic biomass: Process parameters and use of by-products. *Applied Energy*, *144*, 73–95. https://doi.org/10.1016/j.apenergy.2015.01.045

Logan, B. E., & Rabaey, K. (2012). Conversion of wastes into bioelectricity and chemicals by using microbial electrochemical technologies. *Science*, *337*(6095), 686–690. https://doi.org/10.1126/science.1217412

National Dairy Development Board (NDDB). (2022). *Dairy statistics and waste generation data*. Retrieved from https://www.nddb.org