HYDROGEN PRODUCTION FROM DAIRY INDUSTRY WASTEWATER

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ABSTRACT
This study investigates a novel approach for sustainable hydrogen production through the electrolysis of dairy wastewater, utilizing graphite rods as electrodes. The primary focus is on evaluating the effects of varying pH levels and temperatures on hydrogen yield, aiming to optimize conditions for maximum efficiency. Dairy wastewater, rich in organic content, served as the feedstock for the electrolysis process. Graphite rods were employed as the anode and cathode due to their excellent conductivity and resistance to corrosion. The study systematically adjusted the pH of the wastewater to acidic, neutral, and basic conditions using appropriate buffering agents. Additionally, the temperature was varied to understand its impact on the electrolysis efficiency. In the procedure, dairy wastewater was collected, filtered, and characterized for its initial pH, chemical oxygen demand (COD), and total solids. Graphite rods were submerged in the prepared wastewater, and a direct current was applied. The pH was modified to predetermined levels (acidic, neutral, and basic) using buffering solutions. The system was evaluated at different temperatures (20°C, 40°C, and 60°C) to assess the impact on hydrogen production. Hydrogen gas was collected and measured using gas chromatography, and the COD was monitored to evaluate the extent of organic matter degradation. The study found that acidic conditions and higher temperatures significantly enhanced hydrogen production. Optimal hydrogen yield was observed at a pH of 4 and a temperature of 60°C, with a notable reduction in COD, indicating effective degradation of organic pollutants. The findings demonstrated the feasibility of using dairy wastewater for hydrogen production through electrolysis with graphite rods as electrodes. The study highlighted the importance of optimizing pH and temperature to maximize hydrogen yield and contribute to sustainable energy solutions.

Keywords: Hydrogen production, dairy wastewater, electrolysis, graphite rods, pH, temperature, sustainable energy.

I. Introduction

The global energy landscape is undergoing a significant transformation as the world seeks sustainable and renewable energy sources to meet rising demands while mitigating environmental impacts. Hydrogen, often referred to as the fuel of the future, has garnered substantial attention due to its potential to revolutionize energy systems. It offers a clean and efficient alternative to fossil fuels, with water being its only byproduct when used in fuel cells [1]. Among various hydrogen production methods, utilizing waste materials not only addresses energy needs but also contributes to effective waste management [1] . Dairy wastewater, characterized by its high organic content, presents a promising feedstock for biohydrogen production. Dairy wastewater is an abundant byproduct of the dairy industry, containing proteins, fats, and lactose [1]. The disposal of dairy wastewater poses environmental challenges, including high biochemical oxygen demand (BOD) and chemical oxygen demand (COD), which can lead to water pollution and eutrophication if not properly treated [1]. However, its rich organic content makes it an ideal candidate for bio-hydrogen production1. Hydrogen production from dairy wastewater through electrolysis, particularly using graphite rods as electrodes, offers a unique and innovative solution1.

Graphite rods are chosen for their excellent conductivity, stability, and resistance to corrosion, making them ideal for electrolysis in harsh conditions [1]. The process involves splitting water molecules into hydrogen and oxygen gas by applying an electric current, with graphite rods acting as the anode and cathode [1]. The efficiency of hydrogen production can be significantly influenced by factors such as pH and temperature [1]. pH levels affect the availability of hydrogen ions or hydroxide ions, which are crucial for the electrolysis process [1]. Adjusting the wastewater to acidic (low pH) or basic (high pH) conditions can enhance hydrogen production [1]

II. Literature

Fermentative hydrogen production from wastewater and solid wastes using mixed cultures has emerged as a promising solution to address global energy and environmental challenges. This method leverages anaerobic microorganisms, notably Clostridium and Enterobacter, to convert organic matter in waste into hydrogen, a clean fuel that only produces water upon combustion. Mixed cultures are favored over pure cultures due to their cost-effectiveness, ease of control, and broader feedstock compatibility. However, effective pretreatment of seed sludge—through methods like heat treatment, pH modification, or chemical inhibitors—is often essential to suppress hydrogen-consuming bacteria while retaining hydrogen producers. Optimized process parameters, including pH, temperature, and hydraulic retention time, are critical for maximizing hydrogen yield, conversion efficiency, and production rates. This anaerobic process holds advantages over traditional methane production, offering potential applications in sustainable energy generation while aiding in waste management and pollution control.[1]

The reviewed literature highlights wastewater as a valuable feedstock for bio-hydrogen production, offering a dual benefit of energy recovery and waste remediation. Low-energy processes such as photo fermentation, dark fermentation, photocatalysis, microbial photo electrochemical cells (MPECs), and microbial electrolysis cells (MECs) each provide distinct pathways for hydrogen production. Photo- and dark fermentation rely on microbial metabolism, with photo-fermentation requiring light and dark fermentation proceeding anaerobically. Photocatalysis and MPEC utilize catalysts to harness solar energy for hydrogen generation, whereas MEC applies a small external bias to drive microbial activity. These methods can reduce wastewater's chemical oxygen demand (COD) by at least 45%, although achieving optimal hydrogen yields and treatment efficiency remains challenging. Among these technologies, MECs show promise due to their modularity and potential for significant COD reduction, though scalability and cost are hurdles. Future developments emphasize integrating these systems into wastewater facilities to advance sustainable energy and resource recovery efforts [2] The literature on bio-hydrogen production from waste materials emphasizes its potential as a renewable and clean energy source. Traditional methods for hydrogen production, such as water electrolysis and steam reforming, are energy-intensive and costly. In contrast, biological processes, including dark and photo-fermentation, utilize waste materials rich in carbohydrates—such as agricultural residues and food industry wastewaters—as substrates for hydrogen-producing microorganisms. Dark fermentation, driven by anaerobic bacteria, and photo-fermentation, requiring light, offer efficient hydrogen production while contributing to waste treatment. Challenges include the prohibitive cost of raw materials, optimization of microbial strains, and the need for specific conditions (e.g., pH, temperature, light). Utilizing mixed fermentation approaches, particularly sequential dark and photo-fermentation, improves hydrogen yields, while ongoing research into microbial culture improvements and bio-reactor designs continues to advance this eco-friendly energy technology [3]

The literature highlights the potential of wastewater as a renewable source for producing lower carbon hydrogen, which is crucial for sustainable energy transitions. The report extensively reviews various hydrogen production technologies that use wastewater as a substrate. Biological methods, such as dark fermentation and photo fermentation, are found to effectively utilize microbial processes to generate hydrogen while treating wastewater. Additionally, electrochemical techniques, like microbial electrolysis cells (MECs) and photoelectrochemical cells (PECs), offer promising pathways for efficient hydrogen production and environmental benefits. These methods stand out as cost-effective and renewable alternatives to traditional fossil-fuel-based processes, such as steam methane reforming (SMR) and coal gasification, which contribute significantly to greenhouse gas emissions. The integration of hydrogen production with wastewater treatment not only minimizes emissions but also recovers energy, highlighting a dual-benefit approach. Consequently, leveraging these approaches aligns with global sustainability goals by advancing renewable hydrogen production and addressing wastewater management challenges [4]

The literature on fermentative hydrogen production highlights the potential of wastewater as a sustainable feedstock due to its organic-rich content, which can be effectively utilized in anaerobic biohydrogen production. Key technologies, such as dark fermentation, allow for high hydrogen production rates (HPR) without requiring light, making it a viable option across various wastewater types, including sugar-rich, industrial, and toxic wastewaters. Studies show that hydrogen yield and production rates can be significantly affected by factors like pH, temperature, and inoculum conditioning, with optimized conditions enhancing both yield and production rates. For example, techniques like ultrasonication and enzyme pre-treatment can increase yield by improving substrate hydrolysis. Additionally, continuous systems like upflow anaerobic sludge blanket (UASB) reactors have shown promise in scaling up production, though challenges remain in maintaining stable HPR under variable conditions. The use of mixed microbial cultures also enhances resilience and operational flexibility, providing dual benefits of energy recovery and wastewater treatment. Despite technical hurdles, advances in reactor design and process optimization are paving the way for economically viable and environmentally sustainable biohydrogen production from wastewater sources [5]

Electrochemical wastewater treatment has emerged as an innovative method for addressing pollution while simultaneously producing hydrogen and recovering waste heat. Utilizing thin-film diamond electrodes, this approach enables the oxidation of toxic organics on the anode and hydrogen production on the cathode. The resulting hydrogen can be used directly in fuel cells, thereby offsetting energy consumption. As current density increases, the process yields higher rates of both chemical oxygen demand.

(COD) reduction and hydrogen production, although it requires energy management to avoid excessive electric energy use. Additionally, the system recovers waste heat, which can support secondary applications, such as adsorption chillers or heat pumps, thus enhancing overall energy efficiency. This integrated method not only provides a sustainable solution for treating complex wastewaters but also promotes clean energy generation, which is particularly beneficial in industries producing highly toxic effluents [6]

The reviewed report examines the use of anaerobic biofilm reactors, specifically anaerobic packed bed reactors (APBRs) and anaerobic fluidized bed reactors (AFBRs), for hydrogen production from wastewater through dark fermentation. The analysis highlights the significant impact of operational parameters, such as pH, temperature, substrate concentration, hydraulic retention time, and inoculum pretreatment, on hydrogen production efficiency. APBRs and AFBRs are distinguished by their hydraulic properties, with AFBRs showing superior hydrogen production rates due to enhanced substrate contact through fluidization. Various carrier materials, including activated carbon and expanded clay, were evaluated, with porous materials often yielding better results due to their support for biofilm growth. The review underscores the need for controlled conditions to maximize hydrogen yield while minimizing the growth of methane-producing organisms. Overall, the study suggests that APBRs and AFBRs hold substantial potential for sustainable hydrogen production, yet further research is needed to optimize these systems for larger-scale applications using real wastewater samples [7]

The review of biohydrogen production from wastewater and agricultural waste highlights dark fermentation as an effective pathway for renewable hydrogen energy. Using wastewater and agricultural residues, such as beverage waste and mushroom farm by-products, this research assesses process feasibility through simulations in Aspen Plus, emphasizing both economic viability and environmental benefits. The study shows that optimized conditions, including substrate concentration and pretreatment, can yield substantial hydrogen output with high return rates (81% for wastewater and 30% for agricultural waste) under local cost conditions. Capital and operational cost analyses reveal that, while setup expenses are significant, biohydrogen production could be economically feasible at a larger scale. Additionally, hydrogen and CO_2 derived from the process can provide energy and valuable industrial products, with a projected annual revenue from wastewater biohydrogen production of over USD 2 million. This evaluation underscores the potential for integrating biohydrogen production into waste management, offering an alternative fuel source that supports sustainability [8] This study investigates the potential of a new photosynthetic bacterial strain, ZX-5, for biohydrogen production through photo-fermentation, as well as its application in wastewater treatment. ZX-5, a strain of purple non-sulfur (PNS) bacteria, was found to utilize various carbon sources, including succinate, malate, and acetate, achieving hydrogen conversion efficiencies as high as 89.7%. Optimal hydrogen yields were obtained with butyrate, highlighting ZX-5's adaptability to diverse substrates. The study also explored how conditions like pH and light intensity impact hydrogen production. ZX-5 could grow and produce hydrogen over a broad pH range, making it particularly suitable for wastewater environments. In tests on real wastewater samples, ZX-5 demonstrated significant COD reduction and hydrogen yields, indicating its dual functionality as a biohydrogen producer and wastewater treatment agent. This research underscores the potential of ZX-5 as an effective tool for sustainable energy production from waste and organic compounds [9]

The literature review in the provided document discusses the study of biological hydrogen production from olive mill wastewater (OMW) through two-stage processes, highlighting the use of both dark fermentation and clay treatment prior to photo fermentation. The study aimed to address the environmental challenges posed by OMW, particularly due to its high organic load and pollutant content. Researchers conducted two processes: (1) dark fermentation using activated sludge cultures and (2) a clay treatment. Both processes aimed to reduce the toxic effects of OMW to improve hydrogen production. Activated sludge fermentation led to significant hydrogen yields due to organic acid formation, which helped hydrogen production during photofermentation. Similarly, clay treatment improved hydrogen production by reducing OMW's color, thus enhancing light penetration and efficiency of the photofermentative bacteria, Rhodobacter sphaeroides. Comparative analyses showed that coupling dark fermentation or clay treatment with photofermentation improved hydrogen yields over photofermentation alone, supporting the conclusion that two-stage processes offer viable solutions for both hydrogen production and OMW waste mitigation.[10]

The literature review in the document explores the potential of biogas and hydrogen production from the wastewater of Türkiye's milk-processing industry. It identifies that agricultural and industrial wastewaters are rich in organic material and thus ideal for biogas and hydrogen production through anaerobic digestion and steam reforming. The study reveals that Turkey could produce up to 54.2 million cubic meters of biogas annually from milk-processing wastewater, with a substantial economic impact equivalent to approximately $15.1 million in energy savings. Hydrogen production via biogas reforming is highlighted as an efficient process with energy efficiencies between 19% and 70%, and exergy efficiencies ranging from 8% to 48% under optimal temperature conditions (up to 900°C). The paper concludes that with proper processing infrastructure, biogas and hydrogen production could serve as a renewable energy source, significantly contributing to Türkiye's energy demands and reducing environmental impact from wastewater.[11]

The literature review in the document examines biogas and hydrogen production from wastewater generated by the milk-processing industry in Türkiye, focusing on anaerobic digestion and steam reforming processes. This study highlights the potential of milk-processing wastewater, rich in organic materials, for biogas and hydrogen generation. It estimates that Turkey could produce 54.2 million cubic meters of biogas annually from this wastewater, with a value of $15.1 million in energy savings. For hydrogen production, steam reforming of biogas is presented as efficient, with energy efficiencies varying between 19% and 70% and exergy efficiencies from 8% to 48%, depending on conditions like

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steam reforming temperature and ambient climate. The research suggests that biogas generation followed by hydrogen production through steam reforming offers a sustainable approach to managing industrial wastewater, generating renewable energy, and reducing environmental impact. [12]

2.1 Market Size and Growth

The global hydrogen production market is experiencing significant growth, driven by the increasing demand for clean energy solutions and the push towards decarbonization. The market size for hydrogen production was valued at around USD 130 billion in 2021 and is expected to grow at a compound annual growth rate (CAGR) of about 6-8% through 2030. Electrolysis, as a method for hydrogen production, is gaining traction due to its potential to produce green hydrogen when powered by renewable energy sources.

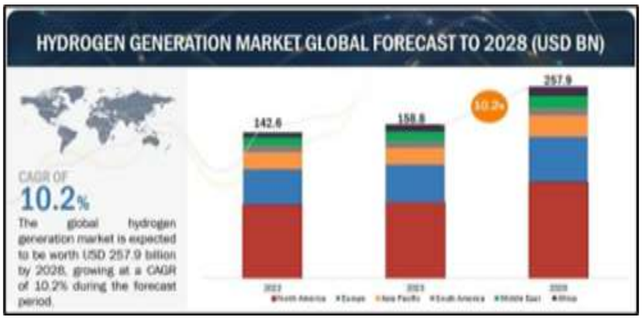

Figure 1. Hydrogen generation market global forecast to 2028(USD BN)

Prospects

Scaling Up Production

- Increase in large-scale green hydrogen projects.
- Cost reductions through economies of scale and technological improvements.

Integration with Renewable Energy

Fig 2. India Hydrogen Market

- Enhanced synergy between renewable energy generation and hydrogen production. Utilization of excess energy for hydrogen production to ensure grid stability.

Physical properties

Properties	Value
Molar Mass	2.016 g/mol
Appearance	Colourless, odourless, and tasteless gas
Solubility in water	1.6mg/L at 20 degree Celsius
Melting Point	-259.16°C
Boiling Point	-252.87°C

Vapor Pressure	It becomes a liquid at exceptionally low temperatures and high pressures.
Thermal Conductivity	0.1805 W/m·K at 300 K
Heat of melting	0.117 kJ/mol
Heat of vaporization	0.904 kJ/mol
Density	0.08375 kg/m³
Refractive index	1.000132
Std Enthalpy of formation	: 0 kJ/mol for H_2 (gas) at standard conditions

Table 1 . Properties of hydrogen

III. Material & Methodology

Materials

1. Electrodes: Two electrodes (anode and cathode), made of graphite or.
2. Electrolyte: A solution to conduct electricity. Power Supply: A direct current (DC) power supply to provide the necessary voltage and current.
3. Water: Dairy Industry Wastewater.
4. Gas Collection System: Test Tubes to collect the hydrogen gas produced at the cathode.
5. Safety Equipment: Safety goggles, gloves, and a lab coat to ensure safe handling of materials and gases.
6. pH Meter: To measure and adjust the pH of the electrolyte solution.
7. Thermometer: Monitor the temperature during the electrolysis process.
8. Voltmeter and Ammeter: To measure the voltage and current applied.

Methodology

Successfully production of hydrogen using dairy industry wastewater is conducted in departmental lab. First, we collected 500 ml of dairy industry wastewater and adjusted its pH to approximately 3, 5 and 9 respectively using hydrochloric acid (HCl) and (Naoh). The prepared dairy wastewater was placed in a beaker, and graphite electrodes were immersed, ensuring they did not touch each other. The electrodes were connected to an AC to DC adapter, further connected to a DC power supply set to a voltage of 12V and a current of 0.5A. Throughout the electrolysis process, the pH and temperature were monitored. Hydrogen gas produced at the cathode was collected using inverted test tubes filled with water, resulting in a collected volume of 7 ml over 30 minutes. Safety equipment was always worn, and the experiment was conducted in a well-ventilated area to prevent hydrogen gas accumulation. After completing the electrolysis, the power supply was turned off, and the electrodes were carefully removed. The treated wastewater was disposed of according to lab waste disposal guidelines. The final temperature remained stable. The consistent production of hydrogen and the recorded volume confirmed the process's efficiency under the set parameters. This methodology provided valuable insights into the feasibility of using dairy industry wastewater for hydrogen production via electrolysis.

3.1 Experimental setup

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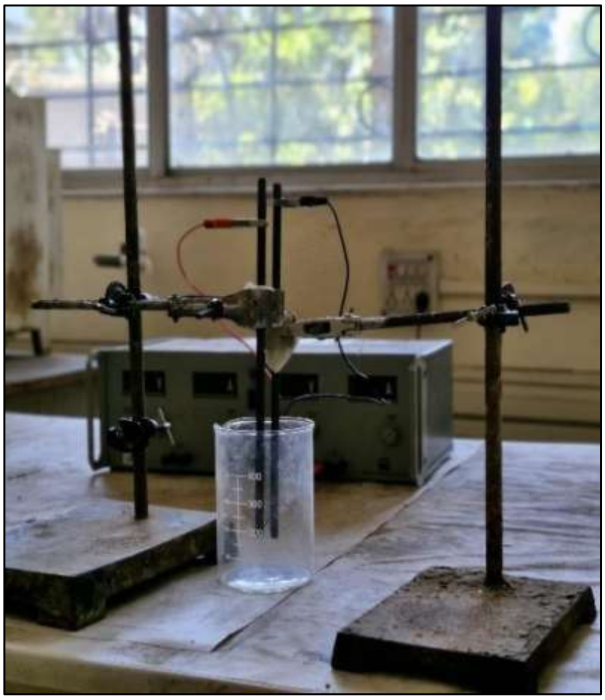

Fig 3.1 Experimental Setup

Electrolysis Setup Specification-
Voltage and Current Settings:
- Voltage: 12V
- Current: 2 A

Electrolysis Apparatus:

- Glass beaker diameter: 7.5 cm
- Distance between electrodes: 1.7 cm.
- Cathode electrode:
- Material: Graphite
- Length: 7 cm
- Diameter: 0.6 cm
- Anode electrode: Corresponding dimensions to
- The cathode

Electrolyte Solutions:
- Raw Dairy Wastewater
  RO Reject Wastewater

Gas collection methods
Water Displacement Method

How it Works: The gas is collected by displacing water in an inverted container. Suitable For: Gases that are insoluble or only slightly soluble in water (e.g., oxygen, hydrogen).
Steps:
- Fill a container with water and invert it in a water-filled basin.
- Connect a tube from the reaction vessel to the inverted container.
- The gas displaces the water, filling the container.

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Air Displacement Method

How it Works: The gas is collected by displacing air in an inverted container. Suitable For: Gases that are insoluble or only slightly soluble in the collecting fluid but react with water (e.g., ammonia).

Steps:

- Use an inverted container and place it in a basin without water.
- Connect a tube from the reaction vessel to the inverted container.
- The gas displaces the air, filling the container.

Gas Syringe Method

How it Works: The gas is directly collected in a gas syringe. Suitable For: Small volumes of gas that need precise measurement (e.g., small-scale reactions).

Steps:

- Connect the reaction vessel to a gas syringe. - The gas pushes the syringe plunger, allowing direct volume measurement.

Composition of Dairy Wastewater and Its Impact on Hydrogen Production

Dairy wastewater is rich in organic and inorganic substances due to milk processing activities. Key components in Dairy wastewater include:

- Carbohydrates (such as lactose) – 0.5-2 g/L
- Proteins (casein and whey proteins) – 0.1-0.6 g/L
- Lipids (fats) – 0.1-0.5 g/L

Microorganisms Involved in Hydrogen Production and Inhibition

The anaerobic microbial community in dairy wastewater includes:

- Hydrogen-producing bacteria: Clostridium spp. (e.g., Clostridium butyricum), Enterobacter spp., and Thermotoga spp. These bacteria metabolize carbohydrates and proteins under acidic to neutral pH, favoring H_2 production.
- Methanogens: These microorganisms (e.g., Methanobrevibacter ruminantium) can compete with hydrogen-producing bacteria by consuming H_2 to form methane, especially in neutral to slightly alkaline pH.
- Acetogens and Sulfate-reducing bacteria: These bacteria (e.g., Desulfovibrio spp.) also compete for hydrogen, reducing H_2 availability by using it in their metabolic processes.

Composition of Dairy Wastewater

1. Total Solids: 4-8%
2. Chemical Oxygen Demand (COD): 50,000 - 80,000 mg/L
3. Biochemical Oxygen Demand (BOD): 20,000 - 40,000 mg/L
4. pH: 4.0 - 5.5
5. Total Nitrogen: 1,000 - 2,000 mg/L
6. Phosphates: 200 - 500 mg/L
7. Sulphates: 1,500 - 3,000 mg/L
8. Potassium: 5,000 - 10,000 mg/L
9. Calcium: 300 - 1,000 mg/L
10. Magnesium: 100 - 400 mg/L
11. Sodium: 500 - 2,000 mg/L
12. Chlorides: 1,500 - 3,000 mg/L
13. Volatile Acids: 2,000 - 4,000 mg/L

IV. Observation & Calculations

Wastewater	Ph Of Water	Temperature	Gas Volume H2 (Ml)
RAW WASTE WATER	8.5	26	1.2
		35	3.3
	9	26	3.3
		35	5.4
	3	26	6
		35	8.4
	5	26	4.2
		35	4.6
RO REJECT	7.5	26	3
		35	
	9	26	3.7
		35	6.2
	3	26	8
		35	9.2
	5	26	6.8
		35	7.1

Table 4. Observation Table

Calculations

1. Efficiency Calculation

Faraday's Law of Electrolysis: This law helps in calculating the theoretical amount of hydrogen produced.

$$m = \frac{I * t * M}{N * F}$$

Where:

- m is the mass of hydrogen produced (g)
- I am the current (A)
- t is the time (s)
- M is the molar mass of hydrogen (2.016 g/mol)
- n is the number of electrons (2 for hydrogen)
- F is Faraday's constant (96485 C/mol) \
- Current (I): 0.5 A
- Time (t): 30 min = 1800 s
- Molar mass of H_2 (M): 2.016 g/mol
- F (Faraday’s constant): 96485 C/mol

2. Yield Calculation

$$\text{Yield} = \frac{\text{Actual } H_2 \text{ produced}}{\text{Theo. max possible}}$$

3. Specific Productivity

$$= \frac{\text{Volume } H_2 \text{ collected}}{\text{COD initial} - \text{COD final}}$$

4. Rate of Hydrogen Production:

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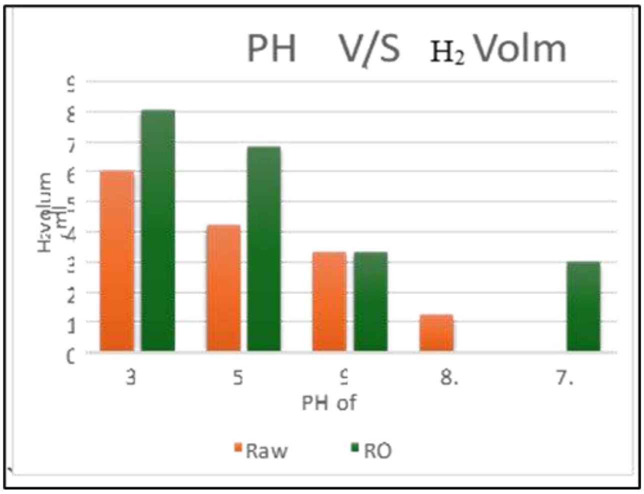
Measure the volume of hydrogen gas collected over a specific period to determine the rate.

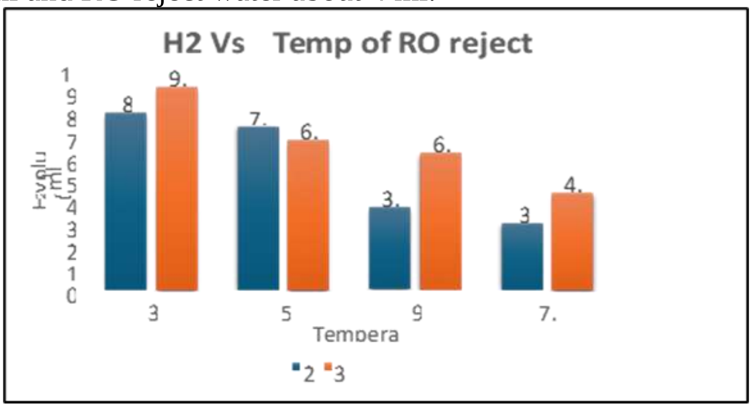
$$\text{Rate of } H_2 = \frac{\text{Volume of } H_2}{\text{Time}}$$



Graph 1. Effect of PH on H2 vol

Graph1. illustrates the effect of pH on hydrogen (H_2) volume generated from two types of wastewaters : raw waste water and revreverse osmosis (RO) reject water. The results indicate a clear difference in H_2 production between the two sources across various pH levels, with RO reject water producing higher volumes of hydrogen, especially under acidic conditions.At pH 3 , RO reject produces the highest hydrogen volume approximately 9 ml, comapred to about 6 ml from the raw wastewater. This suggests that acidic conditions are particularly favorable for hydrogen production in RO reject water. As the pH increases to pH 5, H_2 production decreases slightly for both sources, with RO reject water generating around 7.5 ml and raw wastewater around 4.5 ml. The RO reject water continues to outperform raw wastewater, demonstrating its greater potential for biohydrogen production.

At pH 9, both raw wastewater and RO reject water show a further decrease in H_2 production, with RO reject water yielding about 6 ml and raw wastewater around 3.5 ml. In more alkaline conditions (pH 8.5 for raw wastewater and pH 7.5 for RO reject), hydrogen production is low, with raw wastewater producing around 1 ml and RO reject water about 4 ml.

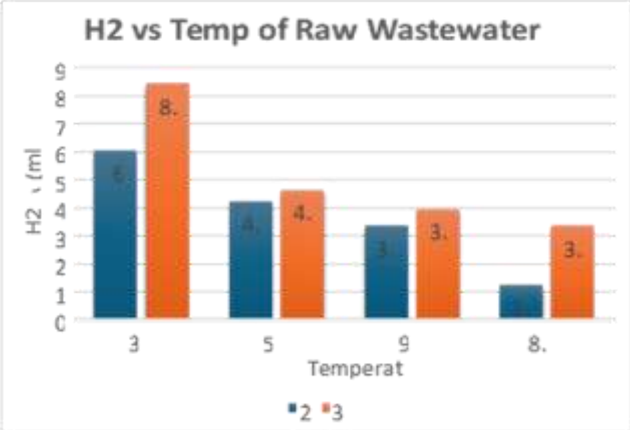


Graph 2. Effect of Temperature change on hydrogen generation for raw wastewater

Graph 2. illustrates the volume of hydrogen (H_2) generated in raw wastewater which was measured at different pH levels (3, 5, 9, and 8.5) and temperatures (26°C and 35°C). The results reveal a clear influence of both temperature and pH on hydrogen production, with higher temperatures and lower pH values favoring H_2 generation. At pH 3, the highest hydrogen volumes were recorded, with 8.4 ml of

H_2 generated at 35°C and 6 ml at 26°C. This trend indicates that acidic conditions and elevated temperatures significantly enhance hydrogen production.

At pH 5, the hydrogen volume decreased to 4.6 ml at 35°C and 4.2 ml at 26°C, suggesting a moderate decrease in production as the pH moves closer to neutrality. As the pH increased to 9 and 8.5 (basic conditions), hydrogen production dropped considerably. At pH 9, 3.9 ml of H_2 was generated at 35°C, while 3.3 ml was observed at 26°C. The lowest volumes of hydrogen were observed at pH 8.5, with 3.3 ml at 35°C and only 1.2 ml at 26°C. This declining trend in H_2 volume as pH rises suggests that basic environments are less conducive to hydrogen production in wastewater.



Graph 3. Effect of Temperature change on hydrogen generation from RO reject wastewater.

Graph 3. illustrates the volume of hydrogen (H2) generated from reverse osmosis (RO) reject water at various pH levels (3, 5, 9, and 7.5) and two temperatures, 26°C and 35°C. The data highlights the impact of both temperature and pH on hydrogen production, with higher temperatures consistently yielding more hydrogen. Hydrogen production was highest at pH 3, yielding 9.2 mL at 35°C and 8 mL at 26°C.At pH 5, production slightly decreased to 6.8 mL (35°C) and 7.4 mL (26°C), while at pH 9 it dropped further.

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Wastewater	Ph Of Water	Temperature	Gas Volume H2 (Ml)	Yield
RAW WASTE WATER	8.5	26	1.2	0.57
		35	3.3	1.578
	9	26	3.3	1.578
		35	5.4	2.51
	3	26	6	2.86
		35	8.4	4.01
	5	26	4.2	2.088
		35	4.6	2.19
RO REJECT	7.5	26	3	1.43
		35	3.4	1.6
	9	26	3.7	1.769
		35	6.2	2.93
	3	26	8	3.28
		35	9.2	4.39
	5	26	6.8	3.23
		35	7.1	3.39

Table 4.1 Yield of Hydrogen

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FARADAY EFFICIENCY

SR.NO	Sample	H2 Observed volume (mL)	Theoretical Volume (mL)	Faraday Efficiency
1	Raw Water pH 3	8.4	104.47	8.04
2	Raw Water pH 5	4.6	104.47	4.4
3	Raw Water pH 9	5.4	104.47	5.17
4	Raw Water pH 8.5	3.3	104.47	3.16
5	RO Reject pH 3	9.2	104.47	8.81
6	RO Reject pH 5	7.1	104.47	6.8
7	RO Reject pH 9	6.2	104.47	5.93
8	RO Reject pH 7.5	4.4	104.47	4.21

Table 4.2 Farady Efficiency

PRODUCTIVITY (ML/G COD)

Sample	Volume H_2 (mL)	COD Initial (g)	COD Final (g)	COD Removed (g)	Productivity (mL/g COD)
Raw Water pH 3	14.5	30	21.5	8.5	1.71
Raw Water pH 5	11	30	23.8	6.2	1.77
Raw Water pH 9	9.2	30	25	5	1.84
Raw Water pH 8.5	6.3	30	26.4	3.6	1.75
RO Reject pH 3	21.5	30	18.2	11.8	1.82
RO Reject pH 5	18.7	30	20	10	1.87
RO Reject pH 9	15.1	30	21.8	8.2	1.84
RO Reject pH 7.5	12	30	23	7	1.71

Table 4.3 Productivity

V. Conclusion

The study effectively explored hydrogen production from dairy industry wastewater, highlighting the significant roles of pH and temperature in determining hydrogen yield. Dairy wastewater, rich in carbohydrates, proteins, and lipids, offers a conducive environment for hydrogen-producing bacteria such as Clostridium spp., Enterobacter spp., and Thermotoga spp. These bacteria efficiently metabolize organic matter under acidic to neutral pH conditions, favoring hydrogen production. Conversely, the presence of methanogens, acetogens, and sulfate-reducing bacteria can inhibit hydrogen production by consuming or competing for hydrogen, particularly under neutral to slightly alkaline conditions. Experimental results demonstrated that reverse osmosis (RO) reject water produces higher volumes of hydrogen compared to raw wastewater, especially under acidic conditions. At pH 3, RO reject water achieved the highest hydrogen yield of approximately 9 ml at 35°C, compared to 6 ml from raw wastewater. As the pH increased to 5, hydrogen production decreased for both sources, yet RO reject water maintained higher efficiency, yielding around 7.5 ml compared to 4.5 ml from raw wastewater. At pH 9, hydrogen production further declined, with RO reject water yielding 6 ml and raw wastewater around 3.5 ml. The lowest production was observed in more alkaline conditions (pH 8.5 for raw wastewater and pH 7.5 for RO reject), where raw wastewater produced around 1 ml and RO reject water about 4 ml. Temperature significantly influenced hydrogen production, with higher temperatures (35°C) consistently enhancing hydrogen yield across all pH levels compared to 26°C. This trend was consistent for both raw wastewater and RO reject water, highlighting the importance of maintaining optimal thermal conditions to maximize hydrogen production.

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