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WASTEWATER TREATMENT AND HYDROGEN PRODUCTION VIA MICROBIAL ELECTROLYSIS CELLS (MECS) AND FERMENTATION METHODS: A COMPARATIVE REVIEW

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ABSTRACT. The rapid increase in human activity in recent years has increased energy demand and waste output. Although wastewater is frequently seen as a problem, it has the potential to be seen as a rich source of resources and energy. An appealing approach to lowering environmental pollution and supplying alternative energy sources is the treatment of contaminants found in wastewater combined with energy recovery. Microbial electrolysis cell (MEC) is one of the most effective waste-to-product conversion technologies available today. There are other methods for wastewater treatment and the production of hydrogen as dark fermentation and photo fermentation. This paper explores the interconnected fields of wastewater treatment and hydrogen production, highlighting their significance in addressing environmental challenges and promoting sustainable development. Various technologies and processes employed in wastewater treatment, such as microbial electrolysis cells (MECs), dark fermentation, and photo fermentation, are discussed in detail. Also, this paper compares MEC, photo fermentation, and dark fermentation for hydrogen production and wastewater treatment. Moreover, it shows some benefits and drawbacks of these technologies. In addition, the integration between these technologies is discussed in this review. Additionally, it provides some descriptive statistics about the outcomes. Finally, some recommendations are presented in the review for future work.

KEYWORDS: Microbial electrolysis cell (MEC); Dark fermentation; Photo fermentation; Photo fermentation integrated with other methods.

1. INTRODUCTION

Due to fast population increase, industrialization, urbanization, and over-exploitation, the quality of the world's water supplies has significantly declined in recent decades [1]. Particularly in the modern era, wastewater (WW) is regarded as a "misplaced resource" from which valuable goods and energy might be produced [2]. Due to the rapid development of industry and the high rate of increase in population, rising global energy demands are an unavoidable problem. Currently, traditional fossil fuel sources supply the majority of the world's energy needs. Two major issues with not sustainable fossil fuel sources are depletion and contamination of the environment [3, 4]. A unique bio-electrochemical device called a microbial electrolysis cell (MEC) uses the organic matter (OM) found in regular wastewater to produce hydrogen gas (H_2). It uses electrogenic bacteria to oxidize OM at the anode, producing carbon dioxide and protons in the process [5, 6]. When a low voltage (>0.2 V) is supplied, the cathode will generate hydrogen by consuming protons and electrons [7]. The two forms of MECs that have been examined the most frequently are single-chamber and two-chamber MECs, which differ in their cell design. Anodic OM oxidation and catholic H_2 generation happen in the same chamber in a single-chamber MEC [8]. As a result, gas contaminants like CO_2, CH_4, and H_2S are frequently present in the collected H_2. These gases are produced by the activity of anodic biofilms, which contain a variety of microbes besides electrogenic bacteria, including methanogens and sulfate-reducing bacteria [9]. Meanwhile, methanogenesis (which turns CO_2 and H_2 into CH_4) will cause a sizeable amount of the created H_2 to be lost [10]. Methanogenesis continues to be a major obstacle to the long-term operation of a single-chamber MEC [11]. The OM oxidation and H_2 generation should ideally configured to occur in various (unrelated) temporal or

spatial domains to avoid such loss and get high-purity H_2. A membrane is employed in a two-chamber MEC to separate the two processes [12]. Other Different microbial electrolysis system types MEC-anaerobic digestion coupled system [13], MEC with anaerobic membrane bioreactor (MBR) (MBR and acidogenic) [14], Thermoelectric micro converter-MEC coupled system [15], Dark fermentation, MFC–MEC coupled system [16], and Microbial reverse-electrodialysis electrolysis cells (MRECs) [17]. Another method for treating wastewater and also the possibility of hydrogen production is through fermentation, which has two types: dark fermentation [18, 19] and photo fermentation [20, 21]. Also, the combination of these two types together is possible [22, 23]. When it comes to Dark fermentation, is a type of indirect technology where a variety of bacterial genera, primarily Enterobacter and Clostridium, use lipids, proteins, lignocellulosic biomass, and carbohydrate sources such as industrial effluent, crop remnants with sugar, and municipal solid waste as the substrate for the dark fermentation to produce CO_2, H_2, and organic acids via the acidogenic pathway. A variety of photosynthetic bacteria, including purple sulfur, purple non-sulfur, and green sulfur bacteria, use the three-step biochemical process of photo fermentation to convert organic substrate into biohydrogen. Anaerobic conversion is comparable to this mechanism. Photo fermentation is distinct from dark fermentation in that it can only happen when light is present. Moreover, the combination of dark and photo fermentation methods has made it possible to boost hydrogen generation rates and provide efficient wastewater treatment (reducing COD). This essay investigates the various techniques for wastewater treatment and hydrogen production, such as MEC, dark fermentation, and photo fermentation. Furthermore, a comparative analysis of MEC, photo fermentation, and dark fermentation is conducted concerning hydrogen production and wastewater treatment. The advantages and disadvantages of these technologies are also examined. Additionally, the integration between these technologies is mentioned in this review. Descriptive statistics regarding the outcomes of these approaches are presented as well. In the end, various suggestions for further development are offered.

2. MICROBIAL ELECTROLYSIS CELL (MEC)

A unique bio-electrochemical device called a microbial electrolysis cell (MEC) uses the organic matter (OM) found in regular wastewater to produce hydrogen gas (H_2). It uses electrogenic bacteria such as (electrochemically active bacteria, exoelectrogenic, and anode respiring bacteria) to oxidize OM at the anode, producing carbon dioxide and protons in the process [5, 6]. When a low voltage (>0.2 V) is supplied, the cathode will generate hydrogen by consuming protons and electrons [7]. The utilization of (MEC) for the treatment of wastewater offers a creative substitute. (MEC) is an innovative and developing device that may generate biohydrogen from a variety of wastewater sources. Two types of (MECs) are discussed in this review such as single-chamber MEC and dual-chamber MEC.

2.1. SINGLE-CHAMBER MEC (SCMEC)

This design for MEC does not have a membrane separating the anode from the cathode. shown in Fig.1 Since MECs are anaerobic, removing their membrane would not affect efficiency [24]. The single-chambered MECs are small and inexpensive, and because they house both electrodes in one chamber, they have lower internal resistance [25]. The chambers of the cathode and anode are meant to be separated by membranes, which additionally assist in minimizing any potential losses related to the membrane [9]. Methanogens' interference, which lowers hydrogen purity by producing methane, is the main problem with the SCMEC [9, 26]. This review shows some studies for SCMEC. In a study on single-chambered MEC, they showed how to use lignocellulose (Bambusa bambos) to produce clean fuel hydrogen through sequential enzymatic treatment and microbial electrolysis in a single-chamber MEC. Additionally, they investigated MEC (V=400 mL) by adding monodisperse nanoparticles of iron oxide (IONPs) to a graphene anode with an area of 100 cm^2. Cellulase was used in a batch hydrolysis process using pretreated Bambusa bambos that had undergone enzyme pretreatment (10% w/w laccase) and had its lignin content reduced by 40.31%. After 96 hours of incubation, the glucose produced (99.54 ± 4 mg/dL) was further processed in a single-chamber MEC outfitted with extremely effective IONPs covered electrodes for the production of hydrogen. To enhance system performance, engineering parameters such as applied voltage (0.6-1.0 V) and mixing characteristics (0-400 rpm) were also examined. In comparison to MEC with an uncoated anode, the MEC with an IONPs coated anode showed hydrogen production efficiency that was 1.14 times higher. the coated anode produced the most hydrogen at 0.02 g (224 mL) per gram of biomass when an applied voltage of 0.8 V was used under the effect of moderate mixing (200 rpm)[27]. In another study, the MEC was tested over 2600 hours (54 cycles), with applied voltages ranging from 0.8 to 2.2 V. In comparison to the control MEC with significant water electrolysis, the results showed that the MEC was stably operated for the first time during 20 cycles

under 2.0 and 2.2 V. Under 2.0 V, the maximum current density was 27.8 ± 1.4 A/m², or over three times what it was at 0.8 V. Without water electrolysis in the MEC, the anode potential in the MEC may be maintained at 0.832 ± 0.110 V (vs. Ag/AgCl) under 2.2 V. Alkaline solution with a pH of 11.2 and a high applied voltage of 1.6 V might produce a lot of hydrogen and have a lot of current flowing through it. The maximum electrical current density of MEC was 42.0± 10.0 A/m² at 1.6 V and pH = 11.2, which was 1.85 times higher than at 1.6 V and pH = 7.0. All of the cycles had an average hydrogen content of 97.2%, showing that methanogenesis was successfully prevented in the MEC at 1.6 V and pH = 11.2. Under high applied voltages, the investment and size of MEC could be significantly reduced with high hydrogen production rates and current densities. [28]. Another study, they employed an integrated reactor to combine anaerobic digestion (AD) with single-chamber microbial electrolysis cell (MEC) treatment to efficiently recover hydrogen utilizing food waste (FW) as substrate Continuous AD-MEC operation resulted in higher hydrogen generation (511.02 ml H_2 g1 VS) than was possible with AD (49.39 ml H_2 g1 VS). In AD-MEC, the electrical energy recovery and hydrogen recovery both reached highs of 96% and 238,7± 5.8%, respectively. The primary elements of FW [lipids, volatile fatty acids (VFAs), carbs, and protein] were analyzed to evaluate the utilization of organic matter to explore the mechanism of the rise in hydrogen production. The clearance rates of proteins and carbohydrates in the soluble phase in AD-MEC were multiplied by 2.3 and 4 times, respectively, compared to AD treatment. The AD reactor combined with the technology of MEC enhanced the utilization of the primary organic material, as evidenced by the 4.7-fold improvement in the removal of VFAs. This study illustrates the potential for lowering FW quantities while simultaneously producing bio-hydrogen [29].

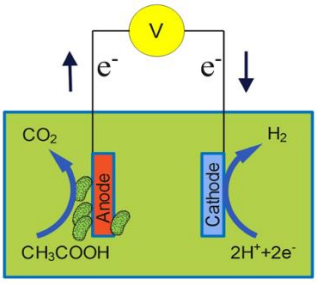

Fig. 1. A single-chamber - MECs schematic

2.2. DUAL-CHAMBER MEC

Typically, anodic and cathodic chambers in double-chambered MEC are separated from one another by a membrane. As shown in Fig.2 The membrane is essential for preserving the hydrogen's purity. It prevents any short circuits and microbial consumption of hydrogen [24, 30]. Proton exchange membranes (PEM), anion-exchange membranes (AEM), cation exchange membranes (CEM), and bipolar membranes are frequently used membranes in MECs[31-34]. The dual chamber configuration's main flaw is the excessive space between the electrodes, which results in substantial overpotentials. Additionally, the membrane's existence causes the imbalance of pH between these two chambers, which raises the voltage losses[35]. This review shows some studies for Dual chamber MEC. In a study, the simultaneous saccharification and fermentation (SSF) of three different lignocellulosic materials were investigated in this work using a dual-chamber (MEC) with concentric cylinders. The maximum hydrogen volumetric output from the mixed substrate was 28.67 L/kg, and the maximum hydrogen production rate (HPR) was 2.46 mmol/L/D with an energy recovery efficiency of 215.33% and a total energy conversion efficiency of 11.29%. During the synthesis of hydrogen, the pH, current, reducing sugar and organic acid concentrations, and pH were all observed in the MEC system. During SSF, the concentrations of reducing sugar, lactate, butyrate, formate, and acetate initially rose and then fell as a result of the creation of hydrogen. Additionally, the combined substrate produced the maximum current, indicating that it is advantageous for microbial metabolism and growth. These findings imply that lignocellulosic materials can be utilized as a substrate in a dual-chamber MEC system with minimal energy input for the synthesis of hydrogen [36]. In another study, two hybrid electrodes alternately serve as the anode and cathode of the MEC while it is in the periodic polarity reversal (PPR) mode of operation. The pH variation is kept within the range of 6.4 to 8.6 when using hybrid electrodes and the PPR mode, and the H_2 generation is 5.3 times higher than it would be in a control with no PPR mode. For maximum H_2 production, a reversal interval of 2 h is ideal. The applied voltage's (0.7-1.0 V) amplitude affects how much H_2 is produced [37].

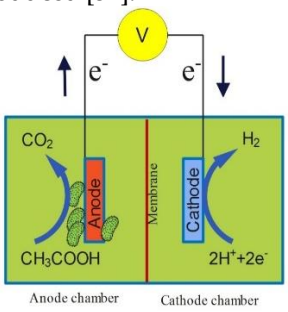

Fig. 2. dual-chamber - MECs schematic.

3. DARK FERMENTATION

Dark fermentation is a form of indirect technology wherein several bacterial genera, mostly Enterobacter and Clostridium, utilize lipids, proteins, lignocellulosic biomass, carbohydrate sources such as industrial effluent, crop leftovers containing sugar,

and municipal solid waste to serve as the substrate for the dark fermentation to create CO_2, H_2, and organic acids via the acidogenic pathway. For example, Abhijit Gadhe et al. [38] presented a sonolysis-enhanced biohydrogen generation from complicated dairy effluent via dark fermentation. Their study explained how ultra-sonication pretreatment can increase the production of biohydrogen from complicated dairy wastewater under previously established, ideal growth conditions. The pretreatment using ultrasonic consisted of 5 different densities of ultrasonic (UD) ranging from 0 - 0.2 W/mL and 5 different times of ultrasonication (UT) ranging from 6 - 14 min. From the methodology of surface response (RSM) study, it was discovered that UD was the very relevant parameter that significantly influenced the improvement of the specific production rate of H_2 (SHPR), biodegradability, and yield of hydrogen (HY) throughout the dark fermentation process. The results revealed that at 0.08 $W.mL^{-1}$ and 9 min, SHPR of 31.38 mmol/g VSS.d and the peak HY of 15.33 mmol/g COD were attained. Finally, the pretreatment of ultrasonication of complicated was roughly 1.1-2-fold more effective than the unsonicated one, according to a considerable relative improvement of SHPR of 51%. and HY of 27%. Another group of E.R. Mikheeva et al. [39] made continuous-flow reactors for the production of dark fermentative biohydrogen from confectionary wastewater. At 37 ± 1 C^o, the dark fermentation process took place. An up-flow anaerobic filter (AF) and a fluidized bed reactor (AFB) were the two reactor types utilized as shown in Fig.3 They found that the greatest output of hydrogen was 44.73 ml/g COD_{init} and a production rate of hydrogen of 92.5 ml/ (L Day) was observed in AFB. Also, the wastewater had a low pH of 3.95 to 4.38.

4. PHOTO FERMENTATION

Regarding photo fermentation, it is the three-step biochemical process that a variety of photosynthetic bacteria, purple sulfur bacteria, purple non-sulfur bacteria, and green sulfur bacteria, use to ferment organic substrate into biohydrogen. This process is similar to anaerobic conversion. Due to the fact that photo fermentation only occurs in the presence of light, it differs from dark fermentation. Thitirut Assawamongkholsiri et al. [40] carried out a repeated-batch fermentation for the generation of lipids and photo-hydrogen from wastewater from a sugar manufacturing facility (see Fig.4). To determine the ideal inoculum size, batch fermentations were carried out in 300 mL serum bottles with a working volume of 180 mL, adjusting the initial concentration of the inoculum from 0.23 – 0.92 gCDW/L. At an initial pH of 7.0, 25.6 C, and 7500 lux of continuous light, photo-fermentation was carried out. The ideal inoculum size was 0.77 gCDW/L, which resulted in 5.24 mL H_2/L.h and production of lipid of 407 mg lipid/L. With a higher lipid output of 424 mg lipid/L, a photo-bioreactor produced a production rate of hydrogen that was 1.73 times higher than that obtained from the fermentation in serum bottles. They also adjusted the ratios of medium replacement by 25, 50 to 75% to study its effect on hydrogen generation. At a medium replacement ratio of 75%, a lipid concentration and maximum biomass of 685 mg lipid/L and 2.83 gCDW/L, respectively, were reached. Finally, the main free fatty acids, C16:0 (9.1 percent), C18:0 (24.9 percent), and C18:1 (51.2 percent) were identified.

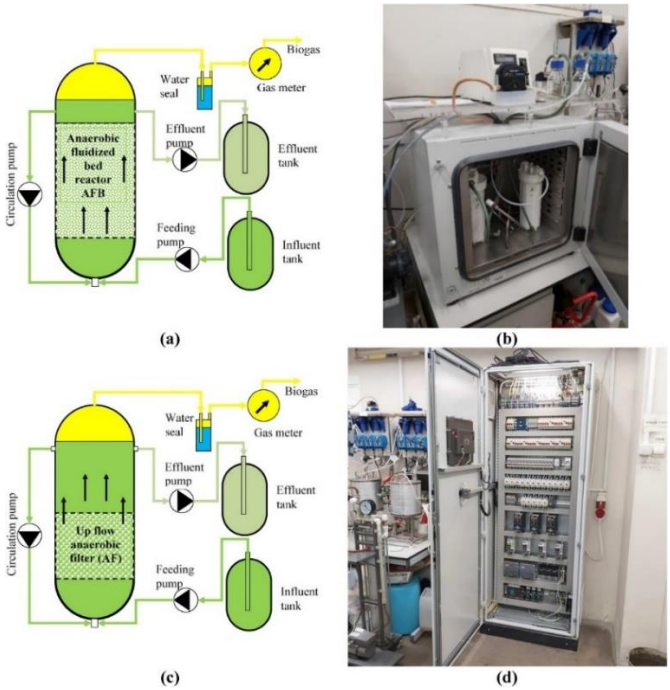

Fig. 3. Schematic with experimental setting of [39].

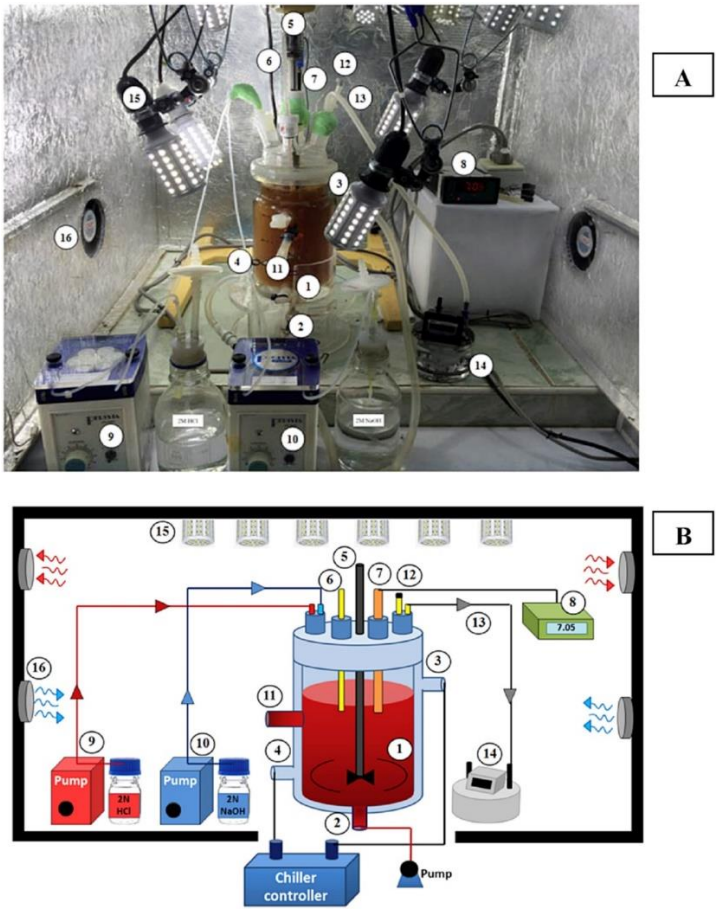

Fig. 4. Diagram and experimental setup by [40].

5. PHOTO FERMENTATION PROCESS INTEGRATED WITH OTHER METHOD

Moreover, it is possible to integrate the photo fermentation process with microbial electrolysis cells as Kaliaperumal Keruthiga et al. [41] who enhanced the production of biohydrogen from rice mill effluent utilizing a synthetic photo-assisted combined with microbial electrolysis unit as it is obvious from Fig.5 using an anode made of waste from the sugar industry. They studied the effects of artificial light and pH on the synthesis of biohydrogen as well as the acid concentration and pH utilized in the acid hydrolysis of wastewater from rice mills. According to the experimental findings, hydrogen production peaked at 220 mL on the fifth day of fermentation, and the average production rate was 3.6±0.4 mL/L/h. Finally, the best biohydrogen output and COD elimination were achieved with an acid concentration of 1.5% and a pH of 6, respectively.

The production rate of hydrogen and for effective wastewater treatment (minimizing the COD), the integration of both dark and photo fermentation processes has come into existence. As an example, Chun-Yen Chen et al. [42] presented a study for the generation of biohydrogen using two-stage sequential fermentation methods: dark and photo (see Fig.6). Utilizing Clostridium pasteurianum of CH_4, dark fermentation was carried out, yielding a maximum of 3.80 mol H_2/mol sucrose in H_2. When applying dark/photo fermentation the overall hydrogen generation increased from 3.80 mol H_2/mol sucrose during dark fermentation to 10.02 mol H_2/mol sucrose. A 72.0% COD removal was also accomplished. Finally, the overall H_2 production of the two-stage process was further improved to 14.2 mol H_2/mol sucrose with an almost 90% COD elimination when the photobioreactor was lighted with side-light optical fibers and augmented with clay carriers of 2.0% (w/v). Another study was introduced by K. Elsharkawy, et al. [43] who treat wastewater from paperboard mills without external chemical addition, combining dark and LED-mediated fermentation as shown in Fig.7 The maximal daily H_2 productivity was found to be 1394.1(± 70.6) mL/L/d. Also, a total efficiency of 58.9(±4.5) % was recorded for substrate removal. Additionally, the effluent from the dark reactor had a pH of 5.5 (± 0.1)

and a carbon-to-nitrogen ratio of 30.0 (± 2.5). Finally, the energetic and financial evaluations highlighted showed a payback period, daily savings, and net gain energy corresponding to 9.8 years, 148.7 $/d, and 1319.5 kWh/d, respectively. Coming to N. Meky, et al. [23], studied the possibility of treating wastewater simultaneously while producing bio-hydrogen (as a fuel provider) by sequential dark and photo-fermentation presented in Fig.8 To do this, they developed a novel configuration known as the reactor dark-photo circular baffled (DP-CBR) and put into operation at room temperature of (21± 10 °C). The reactor was made up of 4 similar compartments, and the last two, C1 to C2 (for dark) and C3 to C4 (for photo), had fluorescent lamps fitted. The long-term influence of primary operating factors (i.e., the time of hydraulic retention (HRT) of 6, 12, & 24 h at starting pH of 5.5 & 6.5) was investigated. At a 24-hour HRT and a 6.5 initial pH, the peak hydrogen output (HY) of 0.4 L/gCOD, 82%COD removal, and 95% Organic-N removal were achieved. Also, it was discovered that raising HRT kept the reactor's efficiency constant at room temperature. In addition, lowering the initial pH to 5.5 made C1 and C2's dark treatment less effective, which reduced local HY and ammonification efficiency. Since protein hydrolysis was primarily accomplished in dark fermentation, the results further demonstrated that higher HY was attained in photo-fermentation. At all tested circumstances, the residual free ammonia concentration (0.36 mg. L-1) was below the level at which photosynthetic bacteria are inhibited.

6. ADVANTAGES AND DISADVANTAGES OF PHOTO AND DARK FERMENTATION AND MICROBIAL ELECTROLYSIS CELL TECHNOLOGIES

Regarding photo fermentation N_2 from the atmosphere can be fixed via photo fermentation. These bacteria can utilize light energy across a broad spectral range. May utilize a variety of organic wastes. but the major challenges of the photo methods are high cost, need for high-intensity light, expensive bioreactors, complex photobioreactor design, low solar energy utilization low efficiency of photosynthetic conversion, challenging practical uses, and oxygen-intolerant photobiological enzymes. Considering dark fermentation however being in the dark, it can continuously create H_2. As substrates, several carbon sources can be utilized. There is no oxygen-limiting issue because it is an anaerobic process. It generates important byproducts as a result, including butyric, lactic, and acetic acids. The major drawbacks of dark fermentation are low H_2 production, low chemical oxygen demand (COD) removal, incomplete substrate conversion, and production of organic acids/ alcohols[44, 45].

The MEC technology has shown to be a great way to recover resources from the wastewater stream produced by different industries and offers several of advantages over conventional treatment techniques. Some benefits of MEC technology include the following: a) The MECs may function with a range of substrates, and the H_2 yields in most MECs are much higher than those of fermentation. Many acetates-based MECs have demonstrated up to 90% hydrogen yields, demonstrating their potential for producing hydrogen [46]. b) The anaerobic digester's CH_4 generation can be increased by using MECs in addition to conventional anaerobic digesters[47]. c) The biorefinery arrangement can incorporate MECs to create hydrogen and recover chemicals. The MECs can help utilize substrates to produce hydrogen and other products with added value and improve the overall effectiveness of the fermentation process if they are placed right after the pre-treatment. Similarly to this, MECs can also be used in conjunction with the method of fermentation to increase the yield of hydrogen and other products[48]. However, there are a few drawbacks to MEC Technology, including a) The configuration of the reactor, the materials utilized in its construction, and the kind of substrate that will be employed in the reactor system all affect how a MEC reactor is set up. Although the conditions for these configurations are specified theoretically, the actual environment may differ and affect the outcomes[49]. Additionally, materials for reactors are expensive, external energy is required, and Energy losses. b) Over time, the yield of H_2 declines as a result of numerous unwanted electron sinks in different metabolisms[50] .c)To ensure that competition among the species of microbes does not impair substrate utilization and product creation, an effective MEC must understand the microorganisms and how they relate to one another. Therefore, it is crucial to have a complete grasp of the bacteria and the behavior that goes along with them[51].

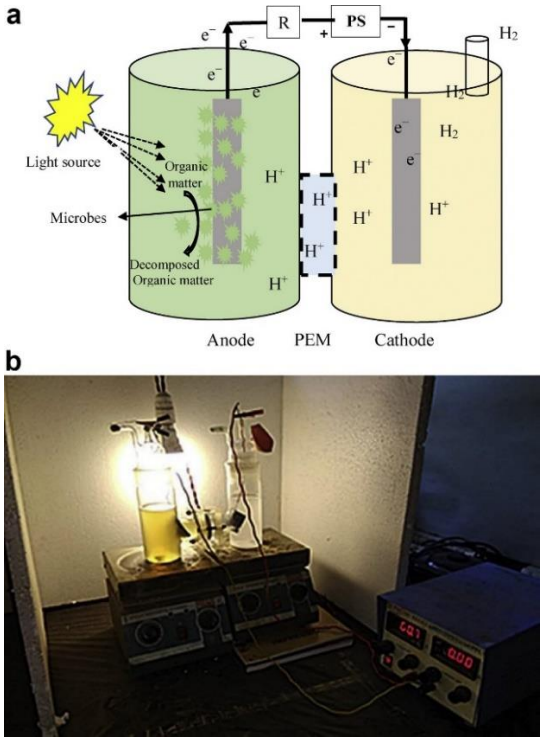

Fig. 5. [41], experimental setup and diagram.

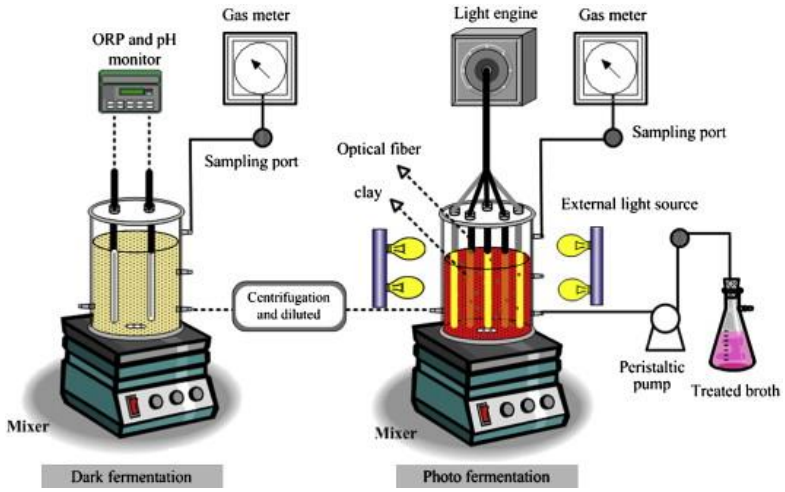

Fig. 6. Diagrammatic explanation of the two-stage process integrating dark with photo fermentation made by [42].

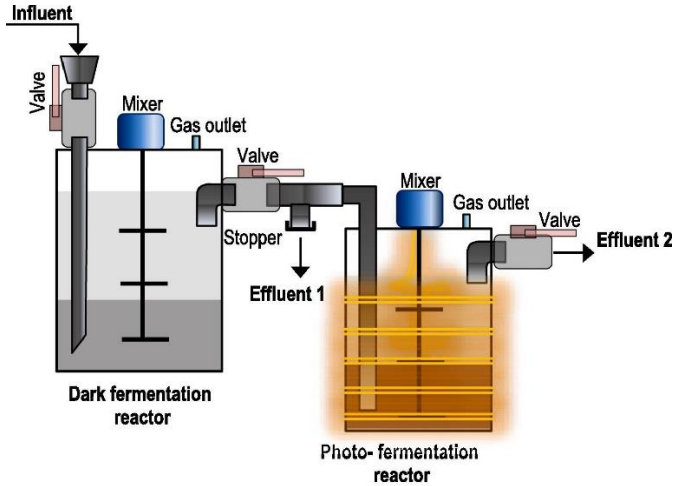

Fig. 7. Illustration of the two-stage technique combining dark fermentation plus photo fermentation of [43].

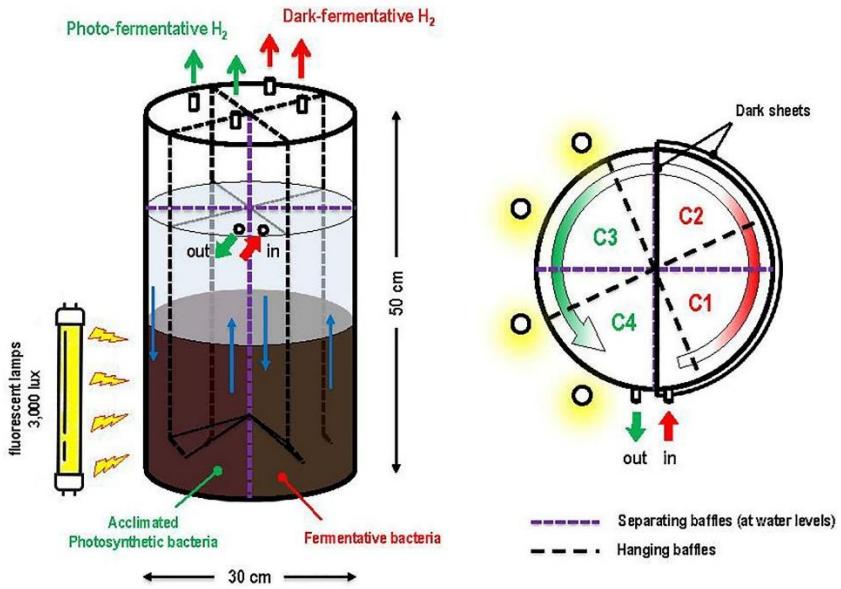

Fig. 8.[23], diagram of the baffled circular reactor of dark-photo fermentation process (DP-CBR), which is used to treat gelatinous wastewater anaerobically.

Table 1. Comparison of several wastewater MECs and fermentation studies.

Ref.	Study type	Effluent type	Type of bacteria	H_2 output L H_2 L^{-1} d^{-1}	COD initial (g/L)	COD final (g/L)	COD consumed (%)	pH
[38]	Dark fermentation	Dairy wastewater	Clostridium spp.	0.7	15.3	10.2	33.33	5.5
[39]	Dark fermentation	Confectionary wastewater	Anaerobic bacteria	0.0925	14 ± 1.5	---	---	7
[40]	Photo fermentation	Wastewater from a sugar manufacturing	Rhodobacter sp. KKU-PS1.	0.126	5.39	---	88.9	7.64
[41]	Photo fermentation-MEC	Wastewater from rice mills	Rhodobacter sp.	0.0864	17.9	---	76.8	6
[42]	Dark- Photo fermentation	Industrial and agricultural wastewater	Clostridium pasteurianum CH4 Rhodopseudomonas palustrisWP3-5	0.76	---	---	90	7
[43]	Dark- Photo fermentation	Wastewater from paperboard mills	Purple non-sulfur bacteria	1.39 ± 0.07 (12h HRT)	---	---	58.9 ± 4.5	5.5
				0.21 ± 0.03 (48 h HRT)	---	---	78.5 ± 4.6	5.5
[23]	Dark- Photo fermentation	Synthetic gelatinaceous wastewater	Photosynthetic bacteria	0.893±0.08 (6h HRT)	---	---	49 ± 5.3 (6h HRT)	6.5
				0.5±0.067 (6h HRT)	---	---	47 ± 2.7 (6h HRT)	5.5
[29]	MEC (single-chamber)	---	Gram-positive and Gram-negative Bacteria	4.86	1419.2 ± 66.4	923.5 ± 3.5	35±2.6	6

[27]	**MEC (single-chamber)**	**Primary sedimentation tank from a wastewater treatment plant**	**Anode-respiring bacteria**	0.047	---	---	---	5
[28]	**MEC (single-chamber)**	**---**	**---**	1.29 ± 0.13	---	---	(72 ± 6)	7
[36]	**MEC (double-chamber)**	**---**	**---**	0.055	---	---	---	7
[37]	**MEC (double-chamber)**	**---**	**Heterotrophic bacteria**	0.11	---	---	---	7.5

7. RESULTS OF THE STATISTICAL DESCRIPTION OF THE DIFFERENT OUTCOMES

Table 2. provides a statistical description of the following outcomes (H_2 output, pH, and COD removal%) in the studies of wastewater treatment and hydrogen production. It was found that the mean of hydrogen production is 0.794 (L H_2 L^{-1} d^{-1}) and the value of the standard deviation is 1.26(L H_2 L^{-1} d^{-1}), which indicates the extent of the difference in hydrogen production for different methods. The minimum value for hydrogen production is 0.047(L H_2 L^{-1} d^{-1}), according to[27], while the maximum value is 4.86(L H_2 L^{-1} d^{-1}) according to [29]. According to pH values, the arithmetic mean is 6.33 and the value of the standard deviation is 0.862, The least value for pH is 5, by [27], however, the highest value is 7.64 by [40]. Coming to COD removal% values it was found that the mean is 62.943% and the value of the standard deviation is 21.19%. The smallest value for COD removal is 33.33% as shown in [38], and the largest value is 90% as shown in [42].

Table 2. Descriptive statistics.

Outcomes	**H_2 output L H_2 L^{-1} d^{-1}**	**pH**	**COD removal%**
Mean	0.794	6.33	62.943
Standard deviation	1.26	0.862	21.19
Range	4.813	2.64	56.67
Minimum	0.047	5	33.33
Maximum	4.86	7.64	90

8. CONCLUSIONS AND FUTURE WORK RECOMMENDATIONS

Wastewater treatment and hydrogen production present promising opportunities for addressing pressing environmental challenges while simultaneously deriving valuable resources. The integration of these two processes offers a sustainable approach to waste management and energy generation. Technologies such as Microbial Electrolysis Cells (MEC), dark fermentation, and photo fermentation have shown great potential in effectively treating wastewater while producing hydrogen. By embracing wastewater as a valuable resource and leveraging the power of microbial processes and sustainable technologies, we can address environmental concerns, contribute to the

energy transition, and pave the way for a more circular and resource-efficient society. Wastewater treatment and hydrogen production offer a win-win solution, simultaneously mitigating pollution and providing clean energy for a sustainable future. This essay examines a few techniques for wastewater treatment and hydrogen production, such as MEC, dark fermentation, and photo fermentation. Also, it compares the production of hydrogen and the purification of wastewater using MEC, photo fermentation, and dark fermentation. And shows some of the technologies' advantages and disadvantages as well. It also displays some descriptive data regarding the outcomes. This paper concludes by highlighting the integration of systems for increasing the production of hydrogen and effectively treating wastewater. Also, the following suggestions are recommended for future works:

- The integration of dark and photo fermentation in the same reactor in an experimental investigation.
- Combing photo-dark rector with MEC reactor.
- Integration of bacteria with algae in the same reactor.
- Determine the optimal hydraulic retention time (HRT) in the dark-photo reactor.

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