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Life-Cycle Assessment Study for Bio-Hydrogen Gas Production from Sewage Treatment Plants Using Solar PVs

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Abstract: Currently, there is a global challenge of water scarcity due to climate change, rising temperatures, and other factors. One way to address this growing global challenge is by implementing technology to treat polluted water by reusing it in areas such as irrigation, cooling, and energy production, based on bio-hydrogen gas. Hydrogen gas can be produced by several methods, including dark fermentation. In this study, hydrogen gas was produced by 1L of sludge and Treated Effluent (TE) with several methods, using a reactor with a volume of 0.96 H_2 L/L media. The Life-Cycle Impact Assessment (LCIA) process was used to study resource depletion, the ecosystem, and human impacts, and efforts were made to reduce the negative impacts by implementing several solutions. In this study, OpenLCA software was used as a tool for calculating the impacts, along with the ecoinvent database. Further analysis was carried out by comparing the LCIA with and without the use of solar energy. The results show that implementing hydrogen gas production with a solar energy system will help to obtain the best solution and reduce the carbon footprint, with 1.12×10^4 kg CO_2 equivalent and a water depletion of 2.83×10^4 m^3.

Keywords: life-cycle assessment; impact assessment; inventory analysis; OpenLCA; ecoinvent database; ReCiPe method; treated water; wastewater treatment; solar energy

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1. Introduction

Globally, there are many issues associated with water scarcity that have a negative effect on humans and on the environment [1]. As a result, it is paramount to find a way of recycling water in order to reduce these impacts. One of the solutions to this is wastewater treatment. Wastewater utilization is one method to decrease the water shortage in many countries [2]. If water is properly treated, it is important to reuse it for beneficial purposes [3]. There are several options for reusing treated effluent [4]. There are several categories for the reusing of treated water, as shown in Table 1 [4], and each option can go through several stages in the treatment process, depending on the quality of the water required [5].

Transferring treated water to the sea is one way of getting rid of water. It is important to know the quality of the treated water so that it does not negatively affect marine life. However, in the presence of water scarcity problems, this method is not considered effective [4].

Water scarcity can be reduced by methods of irrigation, such as reusing treated water for the irrigation [6]. Instead of using groundwater or potable water in agriculture, treated water contributes to saving water and reducing the rate of water scarcity in the world, and is suitable for irrigation. Based on this, forty-four countries around the world use approximately 15 million m^3/day of treated water for crop irrigation [4]. However, there are several parameters that gives brief descriptions of the water quality. These parameters can

affect human health and the environment; they include Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), and others [7]. In view of this, three guidelines in three different years—1973, 1989, and 2005—were provided by the World Health Organization (WHO), with a focus on correct methods for the safe use of treated water in irrigation [8]. The Food and Agriculture Organization (FAO) is also interested in using treated effluent for irrigation [8], as it has issued several guidelines focusing on the water quality suitable for use in irrigation. This is necessary because human health and the soil quality for agriculture in the future could be affected [4].

Table 1. The main treatment stages and categories of wastewater.

Destination	Preliminary	Primary	Secondary	Tertiary
Sea outfall	YES	YES	YES	NO
Irrigation	YES	YES	YES	YES
Potable water	YES	YES	YES	YES
Groundwater	YES	YES	YES	YES
Bio-hydrogen	YES	YES	YES	NO

The reuse of water for drinking is becoming very important worldwide, as it has environmental, technological, and economic impacts. This is achieved by increasing sewage treatment plants in highly efficient ways to ensure high water quality, such as by using Reverses Osmosis (RO) systems that use membranes for increasing the water quality [9], as well as advanced oxidation processes (O_3, H_2O_2, etc.), as sewage treatment plants must be highly efficient and advanced to provide water free of any bacteria. However, the Omani culture is somewhat different, as it is difficult to convince the community to drink treated water. From this point of view, there is no great benefit in treating water with high efficiency if the community is not convinced of the idea [10].

It is possible to transfer treated water to groundwater, thereby increasing irrigation efficiency and improving the quality of agricultural crops. Studies in Oman found that when transferring treated water to groundwater, the area sown with both chickpeas and corn could be significantly increased [11].

Another method for utilizing treated water is by producing hydrogen gas as a source of energy, since nowadays, sources of fossil fuel are decreasing and the world must focus on alternative sources of renewable energies such as hydrogen gas [12]. From 2004 to the present, there have been many studies on the issue of hydrogen gas production, and the Sultanate of Oman has recently begun researching and addressing the idea of hydrogen gas production. Hydrogen gas is considered as a suitable gas in several fields of industry; for example, by 2050, it is expected that hydrogen gas will constitute about 10% of the global demand for heating buildings [12]. The production of hydrogen gas from wastewater is one of the latest methods in the field of energy production, and will contribute significantly to reducing greenhouse gas emissions by 57–73% [13]. Hydrogen can also be produced from wastewater, as this water contains a high percentage of organic matter, which, in turn, is the ideal substrate for microbes to produce bio-hydrogen [14]. This is a suitable way to reduce the pollution resulting from sewage water and also to generate clean energy that contributes to reducing the emissions of greenhouse gases. Wastewater from food processing, dairy products, olive mills, and other sources helps in the production of hydrogen gas [15]. Studies have shown that the production of hydrogen gas depends on several factors, including the type and source of wastewater, treatment technology, operating methods, and production methods [16].

In this paper, hydrogen gas was produced using a reactor with a volume of 0.09 H_2 L/L media, considering several topologies. The sludge and treated-water ratio was varied to generate hydrogen gas considering temperature and hydraulic retention time. Efforts were made to carry out the Life Cycle Impact Assessment (LCIA) in order to ascertain the depletion of the resources involved and find strategies for mitigating impacts on the ecosystem. A further analysis was carried in this study by comparing the LCIA with and

without the use of solar energy. The LCIA can be improved by changing the type of the energy used, since it is clear from this study that electricity is one of the greatest negative impacts of the bio-hydrogen gas production process. The study was carried out in the hybrid OpenLCA and ecoinvent database environment.

1.1. Bio-Hydrogen Production

The increase in the demand for energy and the decrease in the production of fossil fuels has led to the search for other sources of energy that are renewable in nature [17]. Fossil fuels have significant impacts on the environment, leading to an increase in global warming and an increase in temperatures [18]. Therefore, the focus on renewable energy sources has become increasingly important in recent decades, and hydrogen energy has become an interest of many researchers and engineers. Since hydrogen energy does not significantly affect global warming, it is considered to be a renewable energy that relies heavily on organic materials [19].

Bio-hydrogen is produced by specialized microbes used in the reactor. There are several ways in which bio-hydrogen is produced, as shown in Figure 1 [19]. Photosynthesis is the basic function of green plants, as they convert light energy into chemical energy that can be used in all cell activities. In the photo-hydrogen production process, the presence of microorganisms such as diatoms, cyanobacteria, and green algae is necessary, because these microorganisms help to convert light energy into H–H bonds [19].

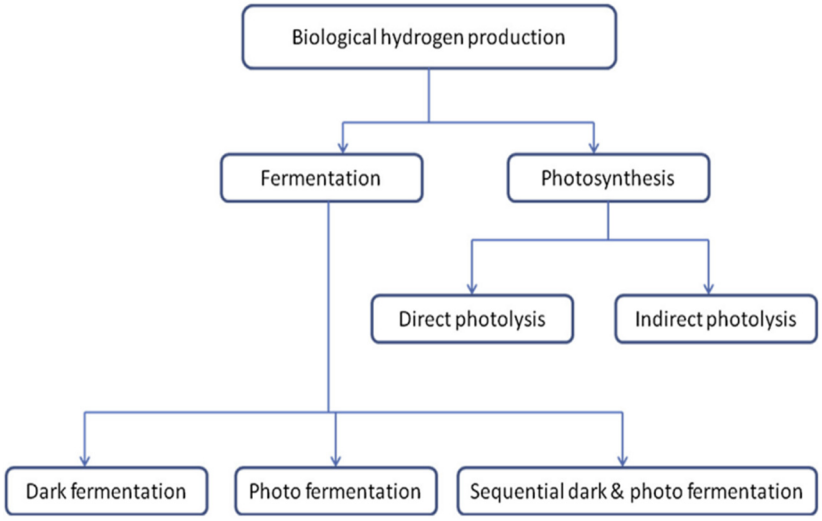


Figure 1. Methods of producing bio-hydrogen.

In direct bio-photolysis, light is absorbed by cyanobacteria called phycobiliproteins. These bacteria contain hydrogen and nitrogen enzymes [20]. The absorbed energy is used to split water molecules into hydrogen and hydroxy; then, the hydrogen atoms combine with each other to produce hydrogen gas [19].

In indirect bio-photolysis, photosynthetic bacteria are used to produce carbohydrates. These bacteria are fermented in the presence of light and then analyzed to produce hydrogen gas [20]. The photosynthesis processes are very cheap and simple. However, the production of hydrogen can have low efficiency [21].

In photo-fermentation, hydrogen gas is produced by anaerobic bacteria; Volatile Fatty Acids (VFA) such as acetic acid, and lactic acid are used as a source of carbon in the presence of light to produce hydrogen gas. There are several advantages of the photo-fermentation process; one is that organic acids have a high conversion rate. On the other hand, using light can make the cost very high, since this will lead to an increase in energy consumption [22]. Because of this, dark fermentation is another way of producing bio-hydrogen. Dark fermentation is used in the absence of light to produce bio-hydrogen from organic matter, considering organic carbon as the energy source. One of the advantages of

this process is that dark fermentation has high productivity, requires only a simple reactor, and uses cheaper substrates. The differences between the dark fermentation and photo-fermentation methods in bio-hydrogen gas production are summarized in the Table 2 [23].

Table 2. Contrast between dark fermentation and photo fermentation processes.

Parameters	Dark Fermentation	Photo Fermentation
H_2	Production of H_2 occurs in substrate degradation.	Production of H_2 occur in substrate synthesis.
Light	There is no need for light intensity.	Light intensity is important.
PH	The best range is between pH 5–7.	The best range is close to pH 7
CO_2	Release of CO_2 gas during H_2 production in the dark and photo-fermentation processes.	
VFA	Generated during the acidogenesis phase in the production of bio-hydrogen.	Can be one of the best substrates for producing bio-hydrogen gas.

1.2. Life-Cycle Assessment (LCA) and OpenLCA Evaluation Software

The International Standard Organization (ISO) provides a series of standards related to the evaluation of life cycle, its definition, and principles in ISO 14040. Life-cycle assessment is a widely used method to assess the environmental impacts of product life cycles and their technological processes, as well as waste management systems and waste disposal processes [24]. Life-cycle assessment is defined as the set of inputs, outputs, and environmental impacts of a particular product throughout its life cycle [24]. The LCA is used as a tool to study and analyze the environmental consequences of a product at all stages of its life cycle, and to try to reduce these consequences [25]. The role of the LCA is to determine the likelihood of environmental consequences occurring in any life cycle and to attempt to reduce these consequences in various ways.

In recent decades, LCA has become an important tool for studying the life-cycle sustainability of any product, especially in research and industry, due to its quantitative nature. It can also help in studying interactions between inputs and outputs and environmental influences [26]. There are many aspects of the ISO 14040 standards for the design and implementation of life-cycle assessment [27]. According to the 14040, 2006, LCA can be divided into four basic stages, as shown in the Figure 2 [26].

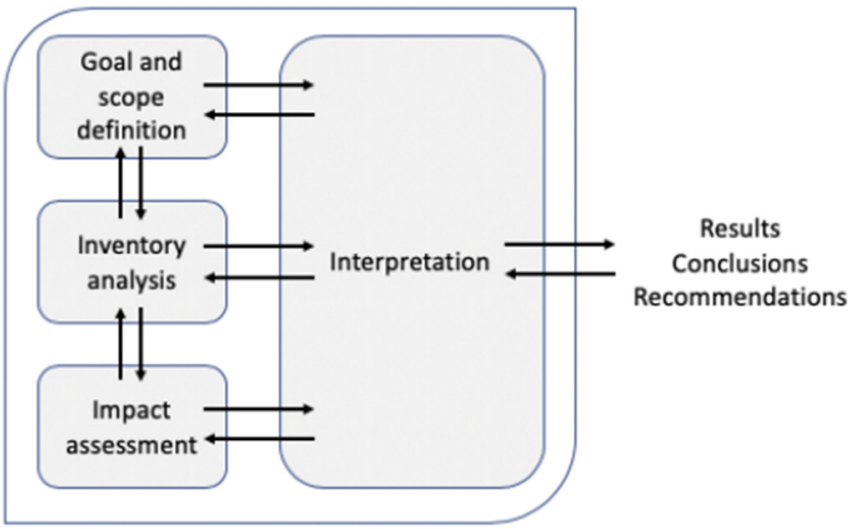


Figure 2. General methodological framework of LCA (Source: ISO 14040).

The OpenLCA application allows the identification of the flow of materials and energy for the manufacture of a product, and facilitates the achievement of the desired goal of the LCA study. OpenLCA is freely available and used for life-cycle assessment and sustainability assessment [28]. It was developed by Green Delta in 2006. Because it is a program available to everyone, it is suitable for sensitive data [29].

One of the main strengths of LCA is its comprehensiveness in the study of environmental impacts, which allows the comparison of many systems, the use of many resources, and the determination of emissions in each system. It helps to find ways to improve the environmental performance of the system, helps decision makers to know the environmental impact of any process, and helps in obtaining benefits from all inputs and outputs [30].

However, there are some challenges facing the use of LCA [31]. LCA is only an estimate of the environmental effects; that is, it is not a real result [32]. Furthermore, the time aspect has another impact on LCA, as the data is taken depending on the steady state. Therefore, the system of evaluation can be affected during the course of the evaluation period, which could greatly affect the LCA scheme employed.

1.3. Solar Energy System

In the last decade, the renewable energy sector has developed immensely in northern countries such as Sweden and Norway, which will be nearly 100% dependent on electricity from renewable sources in the next 5–10 years [33]. Renewable energy is one of the important sources of energy that can help solve many environmental issues such as global warming, greenhouse gases (GHGs), and others. Solar energy is one form of renewable that is converted to electrical power in a clean manner by using photovoltaic systems. India has plans to employ solar energy for around 40% of its total energy, since it is the third biggest contributor of ozone-depleting substances on the planet [33].

2. Material and Methods

2.1. Experimental Set-Up

This study is divided into two main aspects of hydrogen production. The first aspect is about hydrogen production from sludge and treated water. The second aspect is to study the life cycle and find the environmental effects of hydrogen production for use as energy in the future.

The salient part of the hydrogen production experiment used in this study is finding out the effect of an absorber and batch reactor on hydrogen gas production. In this experiment, a reactor was used to produce bio-hydrogen gas from a sample containing 50% sludge and 50% treated water. The reactor was covered for dark fermentation conditions, without using any additional sources of energy such as light or glucose.

The selected Sewage Treatment Plant (STP) in Oman was used as a case study in this paper. In the STP, water can be tested in many locations: before treatment, after the Membrane Bioreactor (MBR) treatment, and after the chlorination disinfection. Therefore, samples can be taken from these three locations and, after the MBR, the selected option can be utilized based on the sludge collected from the sludge collection tank.

Before starting the experiments, the connection between the bioreactor and other parts should be made by connecting the pipes correctly based on Figure 3, as shown in model of the study [34]. In this model, the connections are very important, and they should be made in a proper way to prevent any leakage during the experiment in order to obtain the correct results [35]. Figure 4 shows how the connections are made correctly in the experimental set-up in the Germany University laboratory (GUtech lab, Oman) [36].

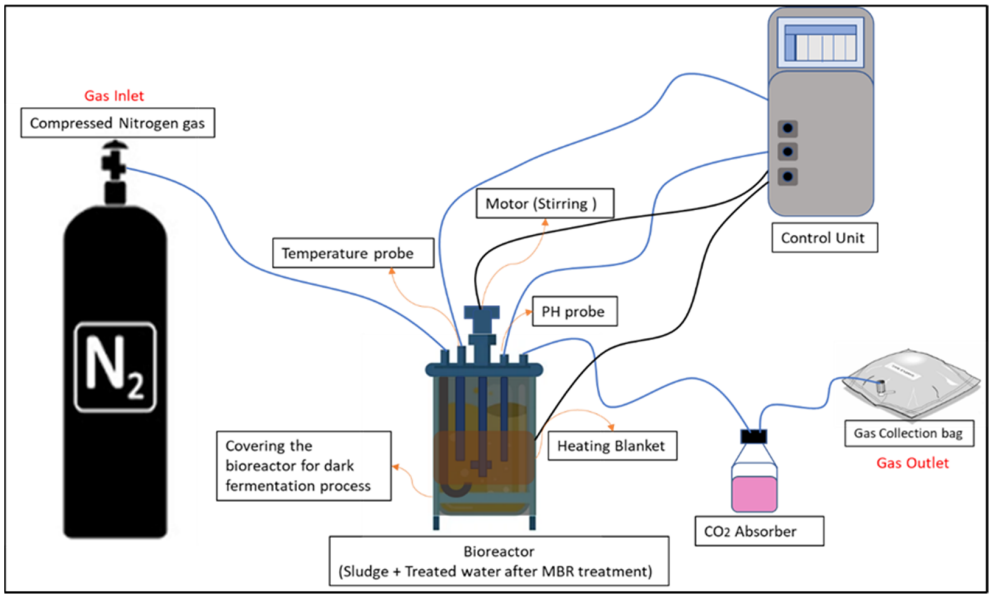


Figure 3. The model of the study.

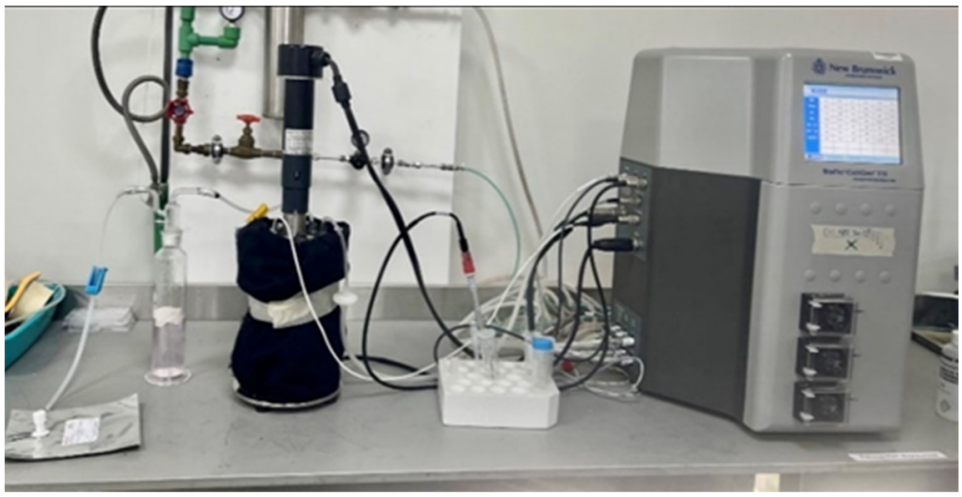


Figure 4. Experimental set-up of the study.

The methodology for producing bio-hydrogen in this study is based on the following process. In this experiment, 500 mL of sludge is mixed with 500 mL of treated effluent in bioreactor. The bioreactor is a BioFlo/CelliGen115 from New Brunswick Company, Oman. Before staring the experiment, it is important to check the connection between the main parts, such as the absorber, gas bag, and the others, with the bioreactor. The check step can be performed using a leak detector. The bioreactor helps in carrying out many functions at the same time. These functions are measuring the value of pH, heating the sample, and bringing the temperature to 37 degrees Celsius. Using the motor for agitation during the fermentation process helps nitrogen gas to flow easily into the sample over about 15 min [37]. The last step is covering the reactor for dark fermentation conditions. The complete details of all these steps are highlighted in Table 3.

Table 3. Summary of the main parameters of the experiment.

Experiment	Sample Composition	Date	Start Time	End Time	Total Quantity
Producing hydrogen gas	TE + Sludge	30 May 2022	15:00	6 September 2022 11:00	500 mL TE + 500 mL Sludge
Experiment	**Initial pH**	**Temperature °C**	**HRT (h)**	**Sparging Time (min)**	**Agitation (rpm)**
Producing hydrogen gas	7.2	37	462	15	100

Gas Chromatography (GC) is a form of analysis that is used to determine a specific chemical component [38]. This component can be gas or organic molecules. In the bio-hydrogen study, after collecting the gases from the experiments, hydrogen gas is separated and analyzed using a GC system. The GC device is a 6890N at Sultan Qaboos University in Oman [39].

2.2. Goal and Scope of LCA

The goal and scope of the first stage in LCA is implemented with the objective of bio-hydrogen production from treated water and sludge [40]. The goal of the LCA is to study the impacts of treating wastewater in STP and to know how the production of bio-hydrogen can affect these impacts, which will help in determining the best practices for reducing environmental impacts and producing hydrogen gas for many fields, especially for industrial use.

The system boundary and the activities of producing hydrogen from STP are carried out in the scope of the LCA. The overall flow diagram of the general system boundary is shown in the Figure 5. From Figure 5, it is clear from the boundary that there are several processes that were not considered, for example, transport of wastewater to the STP, the collection of influents, or disposal of the waste from the grit chamber.

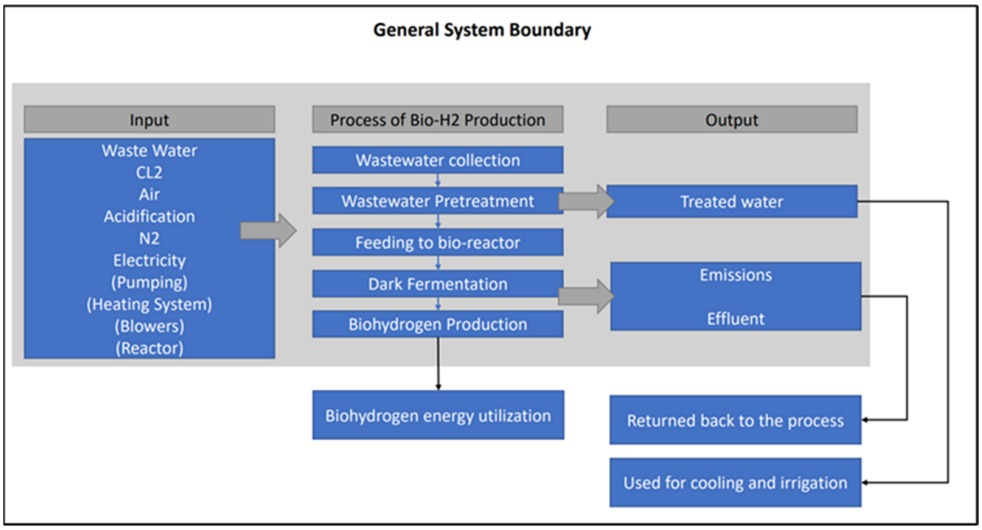


Figure 5. General system boundary of the system.

Figure 6 shows the mass- and energy-flow model of the study. To focus on hydrogen production, the process starts with treated wastewater and removal of the waste from the first clarifier by using the blowers and pumps. Then, it moves to the MBR treatment, which uses pumps, blowers, and a stirrer to complete the treatment. After, the bio-hydrogen production process starts in parallel with the chlorination stage. Finally, the produced products are the bio-hydrogen gas and treated water for irrigation and cooling.

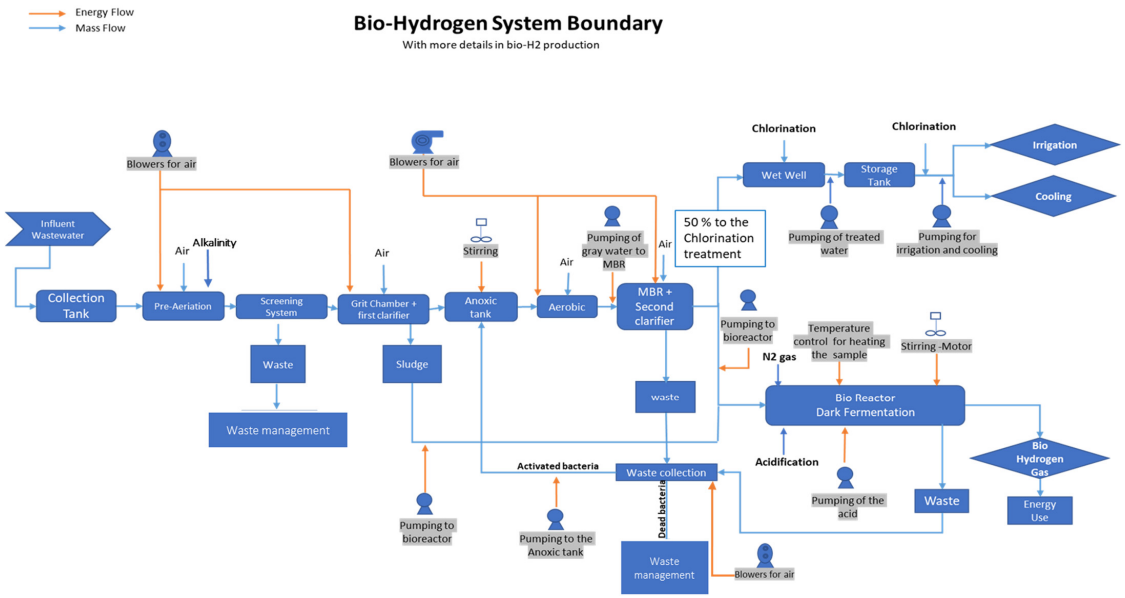


Figure 6. Mass- and energy-flow model.

2.3. Life-Cycle Inventory Analysis

Gathering all the important information is considered in the inventory analysis stage [41]. The data considered in the inventory analysis focus on the energy and mass flows of the STP, which were collected from Oman water authority in (26 May 2022). These flows are actually the outputs and inputs of mass and energy, for example, the energy consumption for blowers and pumps, the amount of chlorine, and others, as shown in Tables 4 and 5.

Table 4. The energy flow of the system boundary.

Number of Units	Name	Location	Energy (kW)	Running Hours (h)	Energy Consumption (kWh)
		Blowers			
3	Blower	Headwork	1.32×10^2	2.40×10^1	9.50×10^3
3	Blower	Biological treatment area	1.50×10^3	2.40×10^1	1.08×10^5
		Pumps			
2	Waste sludge pump	Biological treatment area to bio-H_2 production	2.40×10^0	2.40×10^1	1.15×10^2
3	Transfer pump	Aeration Tank	1.70×10^0	2.40×10^1	1.22×10^2
2	Treated effluent pump	MBR to storage tank (chlorination stage)	6.00×10^2	2.40×10^1	2.88×10^4
2	Utility water pump	TE pump station	3.70×10^1	2.40×10^1	1.78×10^3
2	Bioreactor pump	Bio-hydrogen production area	3.70×10^1	2.40×10^1	1.78×10^3
2	Recycled pump (returned to anoxic tank)	Biological treatment area	1.35×10^1	2.40×10^1	6.48×10^2
3	Pumping of acid	Bio-hydrogen production area	1.50×10^1	2.40×10^1	1.08×10^3
		Mixer			
12	Anoxic tank mixer	Anoxic tank	1.20×10^1	2.40×10^1	3.46×10^3
2	Mixer	Bio-hydrogen production area	6.00×10^2	2.40×10^1	2.88×10^4
		Heating system			
12	Temperature control	Bio-hydrogen production area	1.20×10^1	2.40×10^1	3.46×10^3

Table 5. The mass flow for the system boundary.

No.	Mass Flow	Amount	Unit
S1	Influent wastewater with the recycled water	5.46×10^4	m^3/day
S2	Caustic soda	1.36×10^4	Kg/day
S3	Air	6.46×10^1	Kg/day
S4	Air	1.08×10^2	Kg/day
S5	NaCl	8.90×10^3	Kg/day
S6	HCL	5.23×10^1	Kg/day
S7	N_2	1.70×10^{-1}	g/day
S8	Treated water	2.70×10^4	tonne/day
S9	Waste	2.34×10^2	m^3/day
S10	Bio-H_2	2.19×10^4	m^3/day

2.4. Life-Cycle Impact Assessment (LCIA)

This study was carried out using the OpenLCA 1.11.0 software to find the impact assessment of the conventional process and hydrogen production process. This was achieved by using the ecoinvent 3.6 database from OpenLCA Nexus, with allocation cut-off classification as a system model, since this process focuses on producing a product from waste treatment (i.e., producing hydrogen from wastewater treatment as a source of energy and treated water for cooling and irrigation). The evaluation steps are the last part of the OpenLCA environment, and are important because they help select the best method in terms of the impacts of producing hydrogen from wastewater. There are several methods that can be used to present the data or the results in OpenLCA software. One of them is ReCiPe, which is based on the ecoinvent database. The selected version used in this study was the hierarchist midpoint, which has strong level coherence with a high level of obligatory prescriptions for proving the effects.

The last step in OpenLCA is to obtain the results of each impact category for all the mass and energy flows. Each column shows how each input or output affects the environment. There are many impact categories that OpenLCA computes (about 18 impacts). Each impact has a specific unit, for example, for climate change, the unit is kilograms of carbon dioxide, thus reflecting that carbon dioxide significantly affects global warming processes. All the impacts are gathered and compared before and after implementing the bio-hydrogen gas production. Three of the 18 impact categories were determined in the study. The selection of impacts for interpretation by LCIA was based on studying one ecosystem impact, one human impact, and one resource depletion impacts: climate change, ionizing radiation, and water depletion. The results of the LCIA process help to estimate the future impacts of both processes.

3. Results and Discussion

In this section, the results of the hydrogen production process are analyzed. Additionally, the results of LCIA are discussed considering 18 environmental impacts compared before and after hydrogen production in the processes of the STP. Three of these processes are discussed in detail in this section.

3.1. Analysing The Hydrogen Production

In the three experiments, bio-hydrogen gas production was performed in dark fermentation conditions. The analysis of the hydrogen gas was performed by detecting the presence of hydrogen using the GC analyzer. A calibration step with the GC analyzer was conducted to construct the standards for the hydrogen gas. All the results of analyzing the hydrogen through GC are shown in Table 6. For the photo-fermentation process, which was conducted at the same lab, the hydrogen gas was found equal to 5754 mL H_2/L of the media [42]. This amount is higher than that of the dark fermentation, which was found as 960 mL H_2/L of media. This is because of the source of energy, since in the

photo-fermentation, the bacteria receive energy to produce hydrogen from the light. In dark fermentation, there is no additional source of energy.

Table 6. Results of bio-hydrogen gas production.

Experiment	Amount	Headspace (mL)	Media Space (mL)	HRT	Area
Hydrogen gas production	50% Sludge + 50 %TE	1500	1000	264	31
Experiment	**X Value From (y = 96.7X)**	**H%**	**H_2 in Headspace (mL H_2)**	**Hydrogen Yield (L H_2/L media)**	**Hydrogen Yield Rate (L H_2/L Media/h)**
Hydrogen gas production	0.32	32.05	961.67	0.96	0.004

3.2. Life-Cycle Impact Analysis

Impact analysis is a way of studying the environmental effects of any process. In bio-hydrogen production from wastewater, several environmental effects were studied, constituting 18 environmental impacts, as shown in Table 7. The impacts were studied for the conventional process to compare them before and after implementing the hydrogen gas production. As reflected in the results, negative values mean a positive effect on the environment and on human health, and positive values are considered to be negative impacts. It should be noted that each impact has a specific unit. As seen here, the conventional process can produce around 4.42×10^4 of kg CO_2 Eq. However, this number is decreased with the bio-hydrogen process to around 3.13×10^4 kg CO_2 Eq. Another impact which could be explained is that of fossil fuels; in the conventional process, the fuel consumed is approximately 1.81×10^4 kg Oil Eq. Regarding the hydrogen production process, the fossil fuel consumed is less than in the conventional process, at around 1.72×10^4 kg oil Eq.

Table 7. Analyzing the life-cycle impacts from OpenLCA.

Impact Category	Reference Unit	Result (Conventional)	Result (With Bio-Hydrogen)
Climate change—GWP100	kg CO_2-Eq	4.42×10^4	3.13×10^4
Marine ecotoxicity—METPinf	kg 1,4-DCB-Eq	-3.16×10^2	-4.51×10^2
Marine eutrophication—MEP	kg N-Eq	-1.13×10^3	-1.13×10^3
Natural land transformation—NLTP	m^2	9.00×10^{-3}	-1.06×10^1
Particulate matter formation—PMFP	kg PM_{10}-Eq	-5.04×10^1	-5.58×10^1
Terrestrial acidification—TAP100	kg SO_2-Eq	-1.48×10^2	-1.39×10^2
Terrestrial ecotoxicity—TETPinf	kg 1,4-DCB-Eq	-1.70×10^1	-1.67×10^1
Freshwater ecotoxicity—FETPinf	kg 1,4-DCB-Eq	-4.26×10^2	-4.91×10^2
Freshwater eutrophication—FEP	kg P-Eq	-5.00×10^1	-5.53×10^1
Human toxicity—HTPinf	kg 1,4-DCB-Eq	-8.26×10^3	-7.30×10^3
Ionising radiation—IRP_HE	kg U_{235}-Eq	1.34×10^3	3.14×10^2
Photochemical oxidant formation—POFP	kg NMVOC	-2.05×10^1	-3.81×10^1
Fossil depletion—FDP	kg oil-Eq	1.81×10^4	1.72×10^4
Metal depletion—MDP	kg Fe-Eq	-5.30×10^3	-5.71×10^3
Agricultural land occupation—ALOP	m^2a	5.43×10^2	3.06×10^2
Ozone depletion—ODPinf	kg CFC-11-Eq	1.10×10^{-2}	1.10×10^{-2}
Urban land occupation—ULOP	m^2a	-1.45×10^3	-1.47×10^3
Water depletion—WDP	m^3	-3.83×10^2	-2.81×10^4

As shown in Figure 7, two processes show that climate change has the highest negative impact in terms of greenhouse gases such as CO_2 produced in the next 100 years. It is also notable that the bio-hydrogen process achieves the greatest positive impact in terms of water depletion. Based on these impacts, the main target of the study is achieved, which is utilizing the wastewater and reducing the problem of water scarcity.

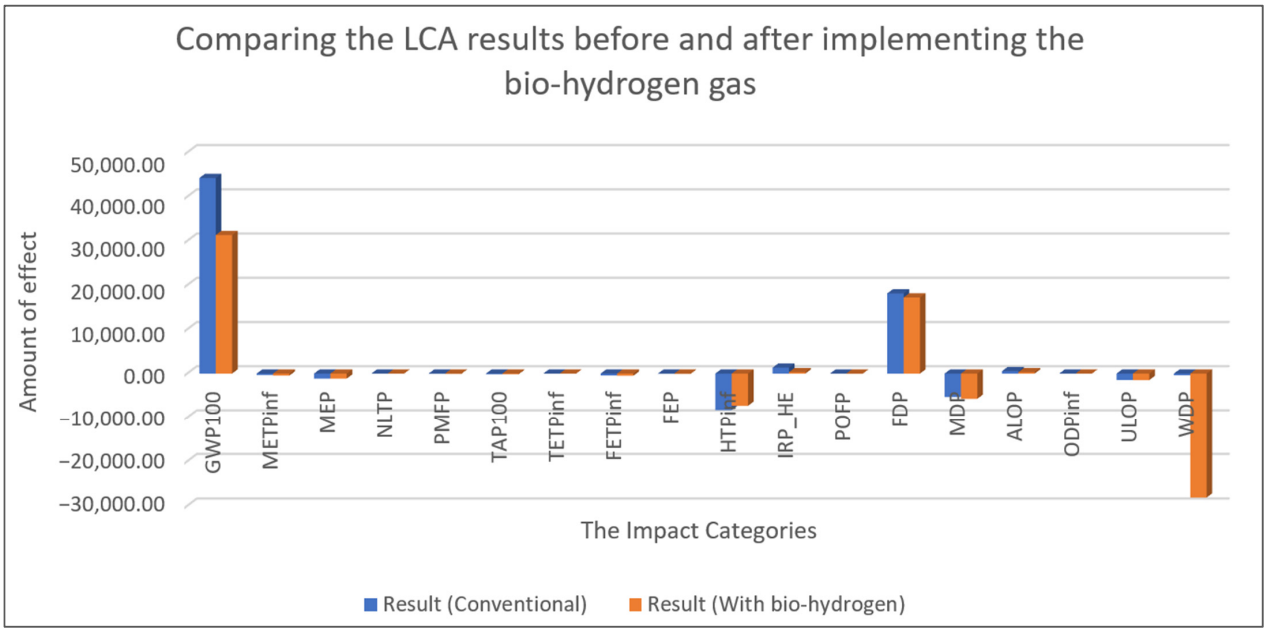


Figure 7. Comparing the impacts before and after the implementation of bio-hydrogen gas.

3.3. Impact Categories

3.3.1. Climate Change

Climate change is one of the impacts based on changes in the temperature and the weather over a long time period. Global warming is one of the results of climate change, which happens due to greenhouse gas (GHG) emissions to the air [42]. Climate change is linked directly to carbon footprint, which reflects the total GHGs that are produced from a specific process. To reduce the impact, it is important to know the main sources of the emissions from the process. For the conventional process, the total emissions are equal to 4.42×10^1 kg CO_2-Eq; for hydrogen production from wastewater, the total emissions are equal to 3.13×10^1 kg CO_2-Eq, as shown in Table 8.

Table 8. Climate change assessment before and after producing bio-hydrogen gas.

Climate Change—GWP100 (ton CO_2-Eq)		
Total amount =	4.42×10^1 tons CO_2-Eq	3.13×10^1 tons CO_2-Eq
Flow	Amount (conventional)	Amount (with hydrogen production)
Electricity	4.98×10^1	4.25×10^1
Sodium hydroxide	1.81×10^1	1.76×10^1
Sludge	4.28×10^0	1.67×10^0
Sodium chloride	2.40×10^0	8.80×10^{-1}
Nitrogen gas	-	7.39×10^{-8}
Treated water	1.63×10^{-9}	-1.55×10^0
Wastewater	-3.04×10^1	-2.98×10^1

From Figure 8, it is clear that electricity produces the highest amount of GHG emissions in the two processes, equal to 4.98×10^1 and 4.25×10^1 for the conventional and hydrogen production, respectively, all in tons CO_2-Eq. Furthermore, it is notable that the emissions from the sludge and sodium chloride in the conventional process are higher than in the hydrogen production process. Table 8 and Figure 8 give all the details of the climate change impact.

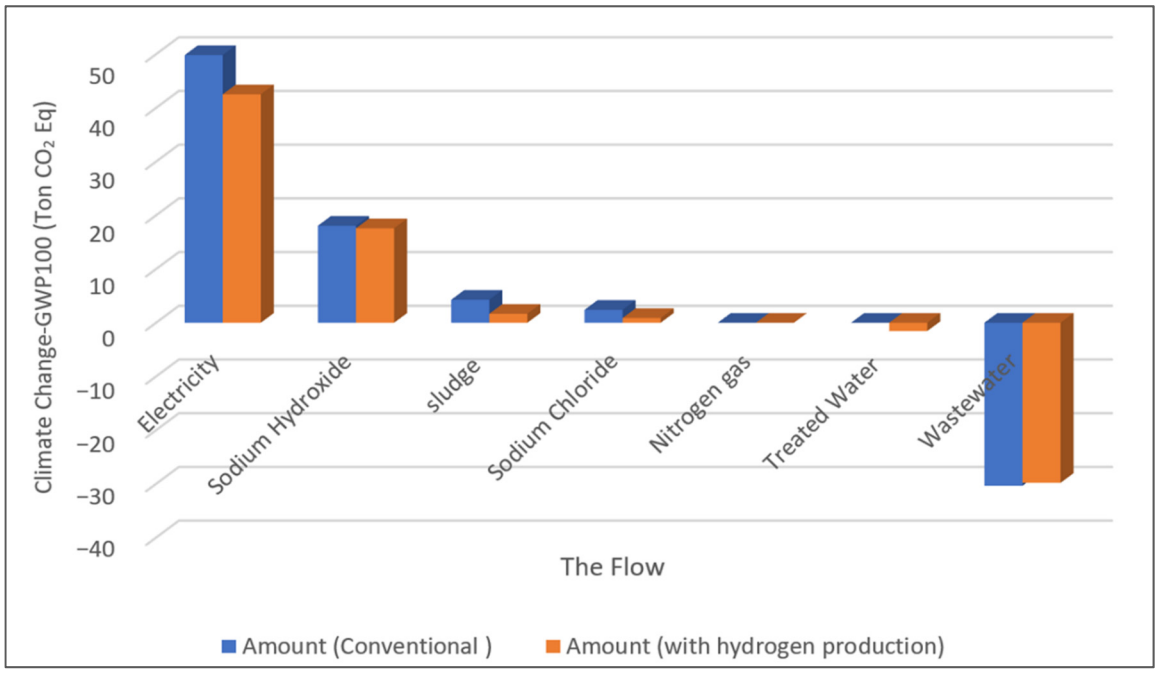


Figure 8. Main sources of climate change impact.

3.3.2. Ionizing Radiation

Ionization radiation is considered as a form of energy from disrupting atoms, creating positive and negative ions such as gamma rays, X-rays, and others [43]. Ionizing radiation can affect humans, animals, and plants by passing radioactive particles through the ecosystem. The unit in this impact is uranium 235 Eq, since this radioactive element can be found in many minerals. According to the focused study, all inventory flows that can affect human health by ionizing radiation are converted to the unit of uranium 235. As shown in the Table 9 and Figure 9, sodium hydroxide has a significant impact on human health and the environment, due to the amount of radiation it produces. The conventional process produces about 2.49×10^0 tons U_{235}-Eq radiation, while in the process of producing hydrogen produces about 2.41×10^0 tons U_{235}-Eq. Table 9 and Figure 9 give more details about the ionizing radiation impact.

Table 9. Details of ionizing radiation impact before and after bio-hydrogen gas production.

Ionizing Radiation—IRP_HE (tons U_{235}-Eq)			
	Total amount =	1.34×10^0 tons U_{235}-Eq	3.10×10^{-1} tons U_{235}-Eq
No.	Flow	Amount (conventional)	Amount (with hydrogen production)
1	Sodium hydroxide	2.49×10^0	2.41×10^0
2	Sodium chloride	2.30×10^{-1}	2.30×10^{-1}
3	Electricity	1.80×10^{-1}	1.80×10^{-1}
4	Sludge	2.90×10^{-1}	1.10×10^{-1}
5	Nitrogen gas	-	7.46×10^{-9}
6	Treated water	-2.5×10^{-7}	−0.83
7	Wastewater	-1.83×10^0	-1.80×10^0

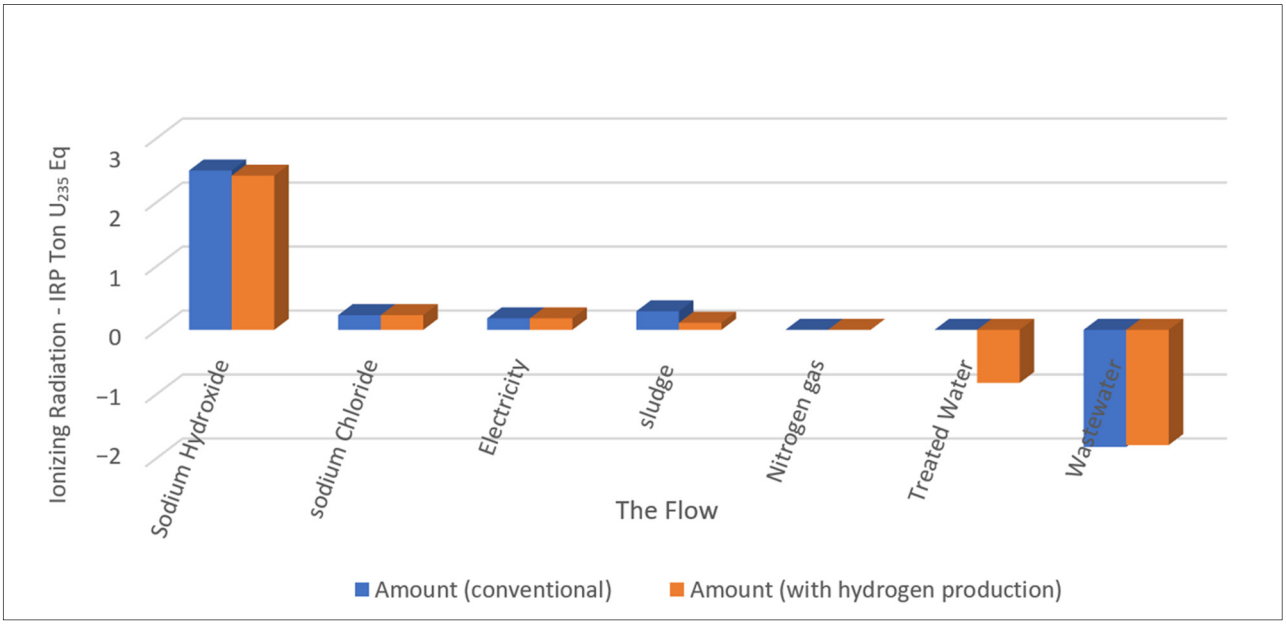


Figure 9. Main sources of ionizing radiation.

3.3.3. Water Depletion

Water depletion shows the amount of the water consumed in the process over the next 100 years. As shown in Table 10 and Figure 10, using electricity can consume around 151 m^3 and 152 m^3 for the conventional process and for hydrogen gas production, respectively. It is clear that the water sent to the sea in the conventional process consumed around 9.37×10^0 m^3 of water, but this amount is significantly decreased with the hydrogen production, to reach around -2.78×10^4 m^3; this is because the treated water is reused for cooling, irrigation, and hydrogen production at the same time. Additionally, water depletion from the NaCl and from the sludge is lower in hydrogen production than in the conventional process. This is because 50% of the sludge is used in the hydrogen production and 50% of the Treated Effluent (TE) is not sent to the chlorination stage.

Table 10. Details of water depletion impact.

Water Depletion—WDP (m^3)			
	Total Amount =	-3.83×10^2 m^3	-2.81×10^4 m^3
No.	Flow	Amount (conventional)	Amount (hydrogen production)
1	Electricity	1.51×10^2	1.52×10^2
2	Sodium hydroxide	7.22×10^1	7.03×10^1
3	Sodium Chloride	1.17×10^1	5.18×10^0
4	Sludge	1.18×10^1	4.62×10^0
5	Nitrogen gas	-	7.86×10^{-7}
6	Waste water	-5.40×10^2	-5.30×10^2
7	Treated water	9.37×10^0	-2.78×10^4

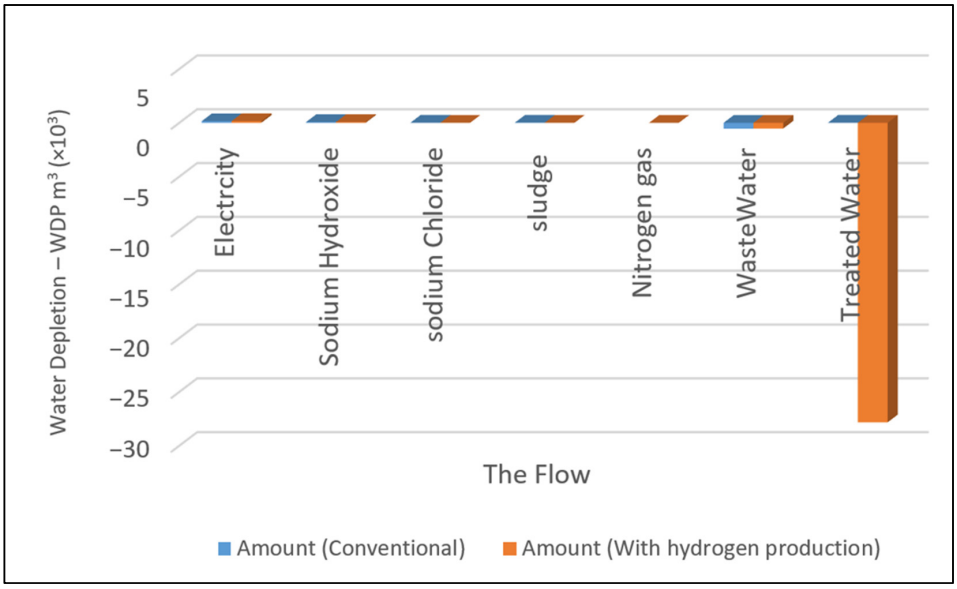


Figure 10. Main sources of water depletion.

3.4. Life-Cycle Impact Assessment with/without Solar Energy

Further analysis was carried out in this part of the study by comparing the LCIA with and without the use of solar energy. The LCIA can be improved by changing the type of the energy used, since it is clear from the study that electricity is one of the highest negative impacts on the bio-hydrogen gas production process. The electricity can be replaced by using solar panels, since Oman is a good location for solar energy due to its weather conditions [44], which are extremely hot during the summer months [45]. The cells can absorb the energy from the sun and change it to electricity to run the STP, as in a similar study with the photo-fermentation process [46].

OpenLCA was used again to confirm that the use of solar energy can reduce environmental impacts, especially the impact of climate change, which describes the carbon footprint. As shown in the Table 11 and Figure 11, the use of solar energy reduces the environmental impacts and has a positive impact on climate change. As shown from the obtained results, without using solar cells as energy, the total amount of GHGs emitted was 3.13×10^4 kg CO_2-Eq, while the use of solar energy reduced these emissions significantly to -1.12×10^4 CO_2-Eq.

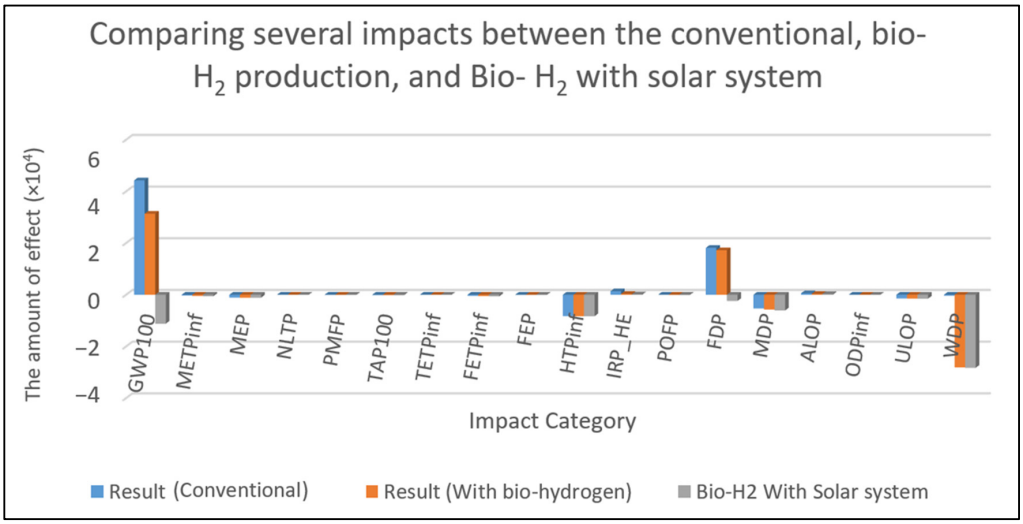


Figure 11. Comparison of the conventional LCIA and H_2 production with/without solar system.

Table 11. Comparison of the LCIA with/without solar energy.

Impact Analysis					
No.	**Impact Category**	**Reference Unit**	**Result (Conventional)**	**Result (With Bio-Hydrogen)**	**Bio-H_2 (With Solar Power System)**
Ecosystem Impacts					
1	GWP100	kg CO_2-Eq	4.42×10^4	3.13×10^4	-1.12×10^4
2	METPinf	kg 1,4-DCB-Eq	-3.16×10^2	-4.51×10^2	-5.64×10^2
3	MEP	kg N-Eq	-1.13×10^3	-1.13×10^3	-1.14×10^3
4	NLTP	m^2	9.00×10^{-3}	-1.06×10^1	-1.84×10^1
5	PMFP	kg PM10 -Eq	-5.04×10^1	-5.58×10^1	-7.01×10^1
6	TAP100	kg SO_2-Eq	-1.48×10^2	-1.39×10^2	-1.76×10^2
7	TETPinf	kg 1,4-DCB-Eq	-1.70×10^1	-1.67×10^1	-1.72×10^1
Human impacts					
8	FETPinf	kg 1,4-DCB-Eq	-4.26×10^2	-4.91×10^2	-6.16×10^2
9	FEP	kg P-Eq	-5.00×10^1	-5.53×10^1	-5.58×10^1
10	HTPinf	kg 1,4-DCB-Eq	-8.26×10^3	-8.30×10^3	-8.31×10^3
11	IRP_HE	kg U235-Eq	1.34×10^3	3.14×10^2	1.26×10^2
12	POFP	kg NMVOC	-2.05×10^1	-3.81×10^1	-8.79×10^1
Resources depletion					
13	FDP	kg oil-Eq	1.81×10^4	1.72×10^4	-2.40×10^3
14	MDP	kg Fe-Eq	-5.30×10^3	-5.71×10^3	-6.07×10^3
15	ALOP	m^2a	5.43×10^2	3.06×10^2	2.62×10^2
16	ODPinf	kg CFC-11-Eq	1.00×10^{-2}	1.00×10^{-2}	8.00×10^{-3}
17	ULOP	m^2a	-1.45×10^3	-1.47×10^3	-1.51×10^3
18	WDP	m^3	-3.83×10^2	-2.81×10^4	-2.83×10^4

The water depletion when implementing the solar power system does not change much; this indicates that electricity has a slight effect on water depletion, while the impact on fossil fuel depletion is reduced significantly. This is because the source of the electricity changes from oil to solar energy. Therefore, the production of hydrogen energy with the provision of solar energy is one of the most important ways to address the 18 effects in a positive way.

4. Conclusions

Wastewater treatment can help to reduce the impact of water shortages globally. Oman is one of the countries working on wastewater treatment to reuse treated water for many purposes, due to its location in a desert region. Bio-hydrogen gas is one sustainable way to reuse the treated water and produce green energy at the same time. Bio-hydrogen production can be achieved through different methods; one is dark fermentation, where the production of hydrogen depends just on the bacteria in the wastewater. However, for any process or any system, it is important to study the impacts and try to form a good recommendation to reduce negative effects.

The Life-Cycle Assessment (LCA) is one of the methods used to study the environmental impacts for any process. This study used OpenLCA software to study the LCA process, using ecoinvent as a database to complete the study and find the results. Studying the impacts of the life cycle of any process is important to be able to know whether the process negatively affects the environment and human life. In this study, the effects were analyzed and ways to reduce them were proposed by calculating the impacts based on the various category indicators using OpenLCA software and the ecoinvent database. As shown in the result, the scenario of hydrogen production with solar power is the best option, since this process will help to reduce water consumption by 2.83×10^4 m^3 and the carbon footprint by 1.12×10^4 kg CO_2-Eq. Thus, this study is in line with Oman's Vision 2040, considering

the fact that hydrogen will be a major transformational step in the field of energy in the Sultanate of Oman.

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