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Techno-Economic Analysis (TEA) of Biohydrogen Production from Palm Oil Biomass Waste

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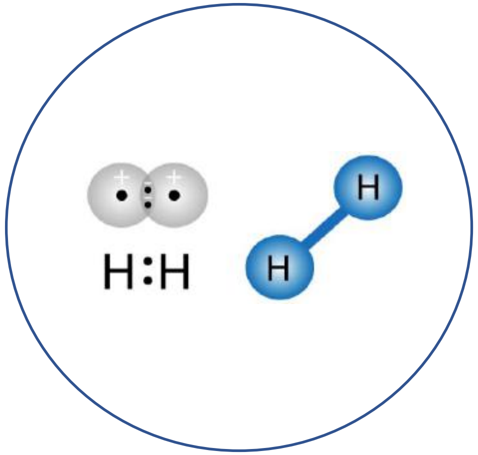
Presentation Outline

01

BACKGROUND

What is hydrogen and biohydrogen?

It is the most abundant, simplest and lightest chemical element (Helen et al, 2020). The prefix “bio-” simply indicates biological source to produce hydrogen



What are the uses/ applications of hydrogen?

Used mainly as energy carrier, power generation e.g. in fuel cell (Bakhtyari et al., 2018). Application in various aspects of chemical, petrochemical, metal industries, etc.

Why use hydrogen?

It is renewable, sustainable and a clean source of energy (in fuel cell, it produces only water which do not pollute the environment) (Singh et al., 2020)

Why and how to produce hydrogen?

Hydrogen does not exists freely in nature as it is very reactive. It always come in compounds such as hydrocarbons as well as water, and other organic substances (hence named energy carrier).

Hydrogen can be extracted/produced from these compounds compound via electrolysis (hydrolysis), thermochemical, biological processes (Martinez-Burgos et al., 2021)

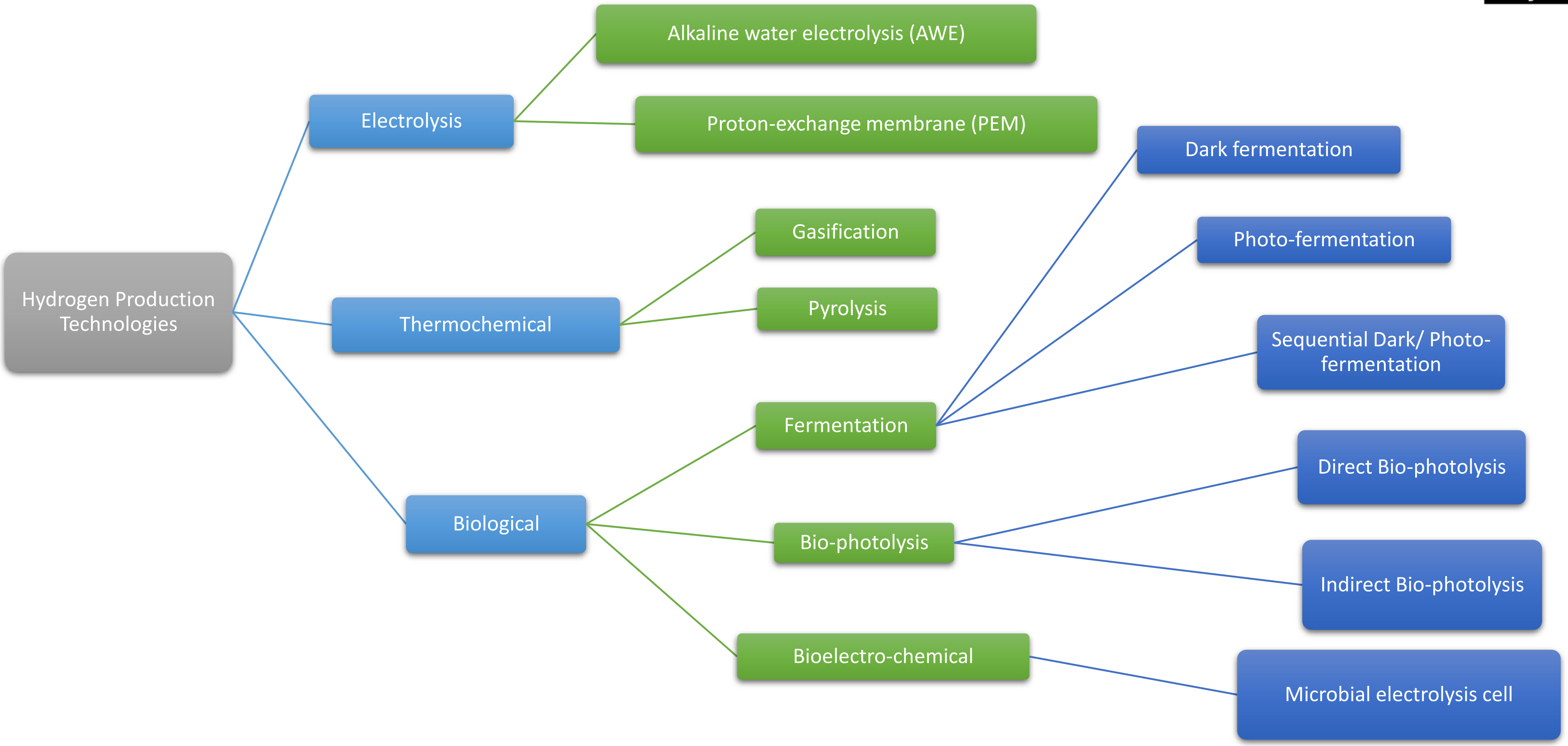


Figure 1: Overview of the available hydrogen production technologies (figure adapted from Kannah et al., (2021, 319)

What is techno-economic analysis?

It is a method to of **analyzing the economic performance** of an industrial process, product, or service. It typically uses software modeling to estimate capital cost, operating cost, and revenue based on technical and financial input parameters.

Technical

- Process simulation
- Mass balance
- Equipment selection and sizing

Economical

- Economic parameters (TCI, AOC, NPV, PBP, IRR)
- Sensitivity analysis

Environmental

- Production of by-product

TCI Total Capital Investment
AOC Annual Operating Cost
NPV Net Present Value
PBP Payback Period
IRR Internal Rate of Return

Curtin University
Malaysia

02

MOTIVATION AND OBJECTIVES

Main Motivation

Development in palm oil industry **increased the production of oil palm biomass wastes**. It is desirable to turn this wastes into valuable products. One of the viable products is **biohydrogen**, which is currently raising in demand. Currently there are limited studies conducted on the techno-economic performance of biohydrogen production from palm oil biomass waste.

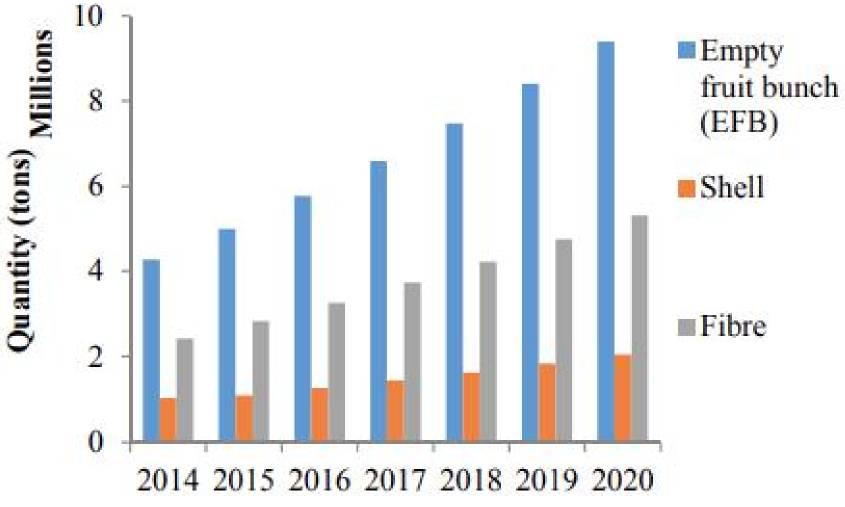


Figure 2: Projection volume of biomass production (Aghamohammadi et al, 2016)

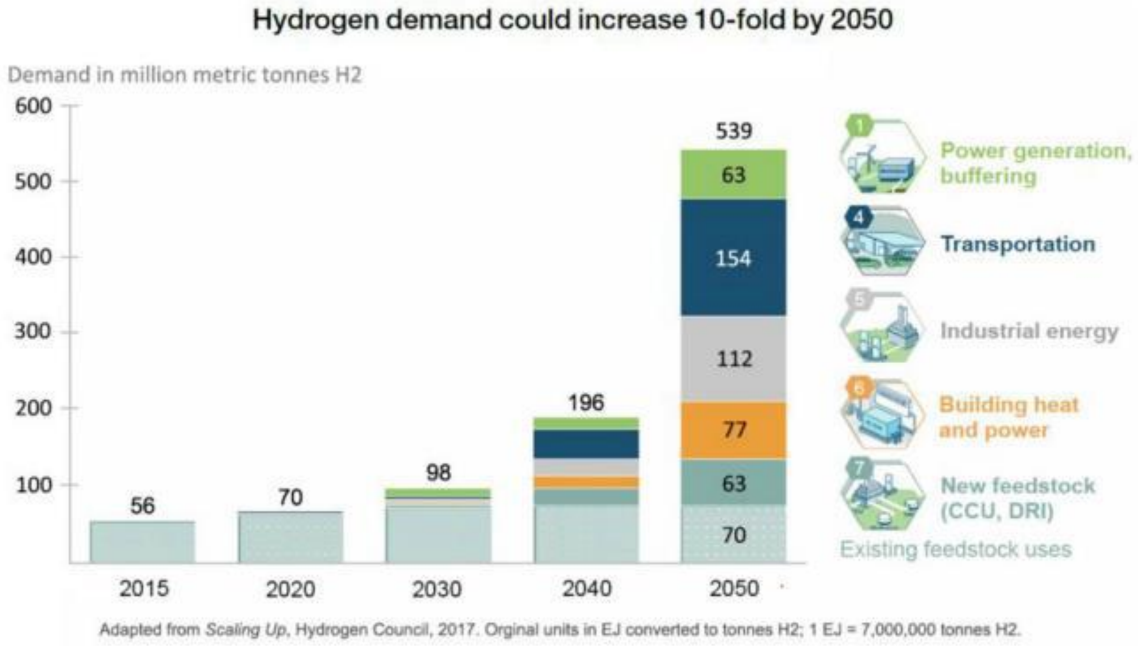
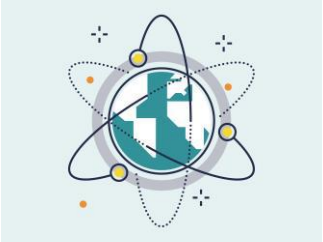


Figure 3: Global hydrogen demand projection (Eljack & Kazi, 2021)

Specific Motivation/Research Gaps

1. Lack of comparisons on the **practical process (biological process)** to **produce biohydrogen** from **palm oil biomass wastes** on a larger commercial scale

2. Lack of studies on the **techno-economic and environmental analysis** of the biological **biohydrogen production from palm oil biomass waste**.



3. Lack of **comparison studies** for the **biohydrogen production** from various **sources** in terms of **technical, economic, and environmental** aspects.

Research Questions

Research Gap 1 →	Which is the **most practical biological way** to produce **biohydrogen** from **palm oil biomass waste** on a larger commercial scale?
Research Gap 2 →	How to perform a **techno-economic analysis** for the biological **biohydrogen production** from **palm oil biomass waste**?
Research Gap 3 →	How does the **biohydrogen production** from **palm oil biomass waste compare to other studies** in terms of **technical**, **economic**, and **environmental** aspects?

Objectives

1. To compare and find a **practical biological process** to **produce biohydrogen** from **palm oil biomass wastes** on a larger commercial scale and develop the process description.

2. To **simulate the biological process** of biohydrogen production from palm oil biomass waste and perform a **techno-economic** analysis.

3. To **compare the analysis results** (in terms of the **technical**, **economic**, and **environmental** aspects) from this study with those from the literature.

03

METHODOLOGY

Research Methodology

Phase 1:

Process selection and development

↓

Objective 1

Phase 2:

Process simulation

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Objective 2

Phase 3:

Process analysis and comparison

↓

Objectives 2 & 3

Selection of Feedstock and Process/Technology

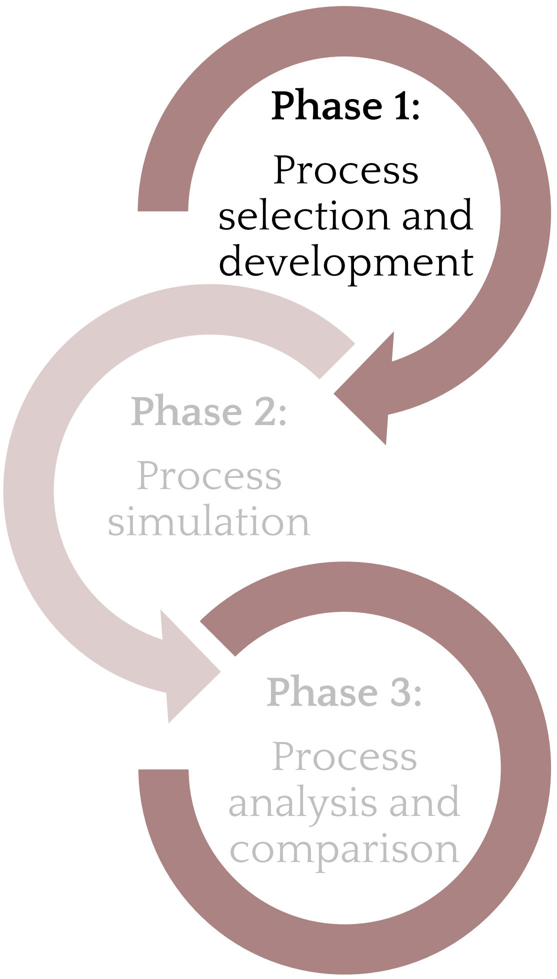
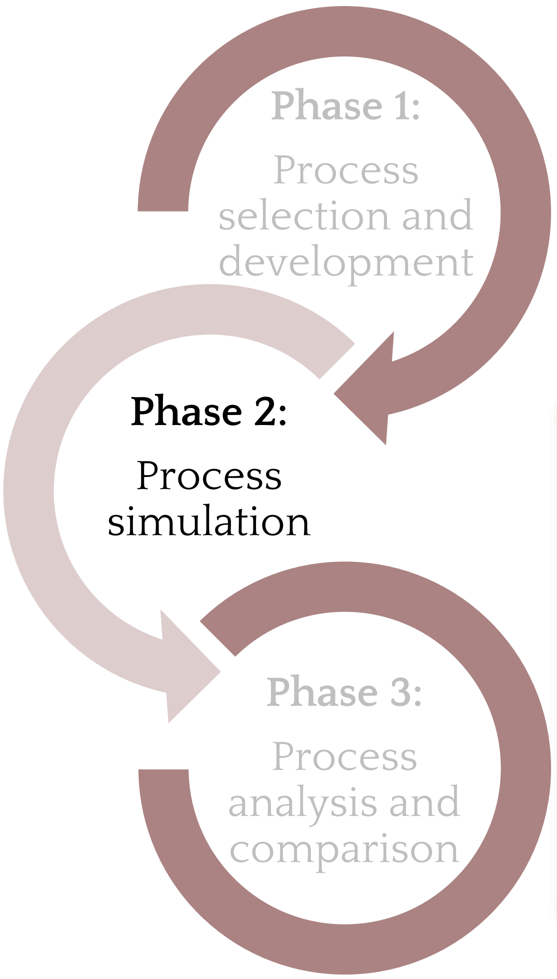


Table 1: Selection of feedstock and process for the conversion of palm oil biomass waste into biohydrogen

Material	Description	Justification
Feedstock	Oil Palm Empty Fruit Bunch (OPEFB)	• Low-cost. • Abundance and high accessibility. • Reduce solid waste disposal concerns. • Great potential for reuse
Process	**Description**	**Justification**
Biological process	Dark fermentation	• Simpler process involving simple reactor and small area • Able to go without light energy (lower cost) • Relatively high hydrogen production rates

Basis of Simulation



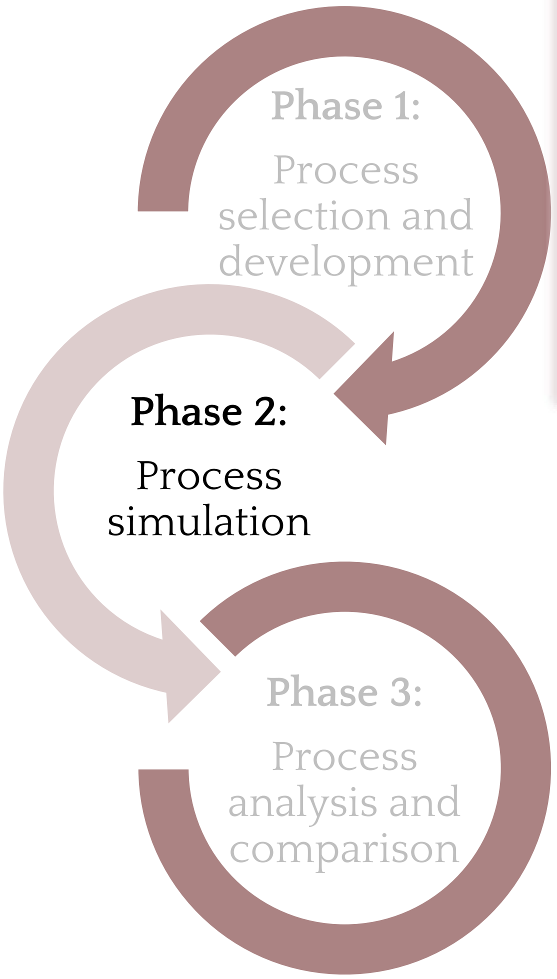
Software

- **Aspen Plus V10** (according to the manual mass and energy balance calculations in Microsoft Excel).

Property Method

- **Non-Random Two Liquids (NRTL)** (commonly used for investigating activity coefficient with the consideration of non-ideal liquid phase). Moreover, the degree of polymerization of the component involved in the process is either hexamers or dimers. Therefore, NRTL is an appropriate choice for this process

Basis of Simulation



Component Input

- Self-defined components: Cellulose, hemicellulose, lignin, ash
- Other components (water, xylose, glucose, hydrogen, acetic acid, carbon dioxide) are in the databanks of Aspen Plus software.

Simulation Parameters

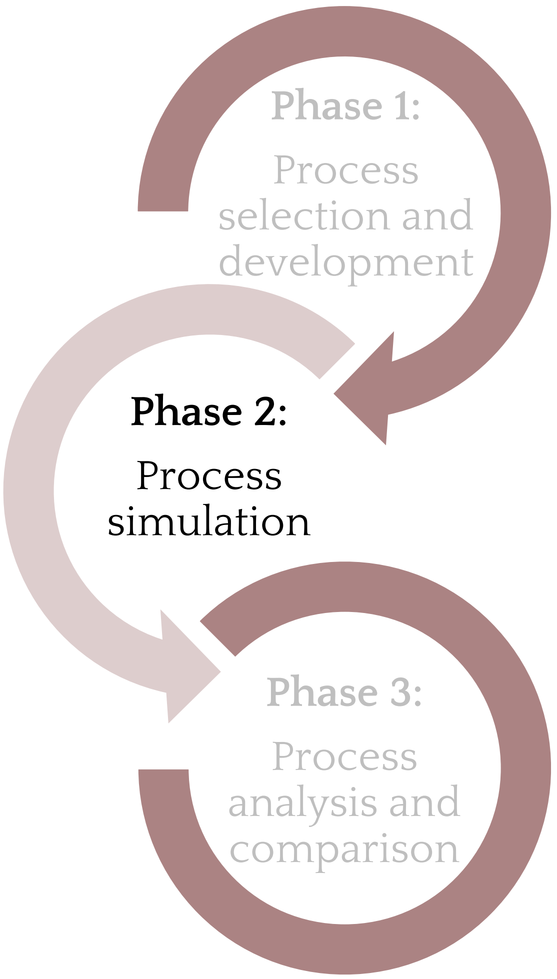


Table 2: Simulation parameters from various steps in the conversion of oil palm biomass waste into biohydrogen

Parameter		Value
Feedstock	OPEFB (cellulose 45.06%, hemicellulose 28.51%, lignin 12.39%, ash 14.04) (Huzairi et al, 2012)	10,000 kg/h
	Water	10,000 kg/h
Physical pre-treatment	Temperature	25 ^oC
	Pressure	1.03
	Standard deviation	0.5 cm
	Particle size distribution D50	20 cm
Enzymatic hydrolysis reaction (Aslanzadeh 2014; Hu et al. 2016)	Temperature	35 ^oC
	Pressure	1.1 bar
	Conversion	80%
Dark fermentation reaction (Foglia et al. 2011; Swain et al. 2019; Andres and Ariel 2019)	Temperature	35 ^oC
	Pressure	1.1 bar
	Conversion	85%

Equipment Sizing and Description

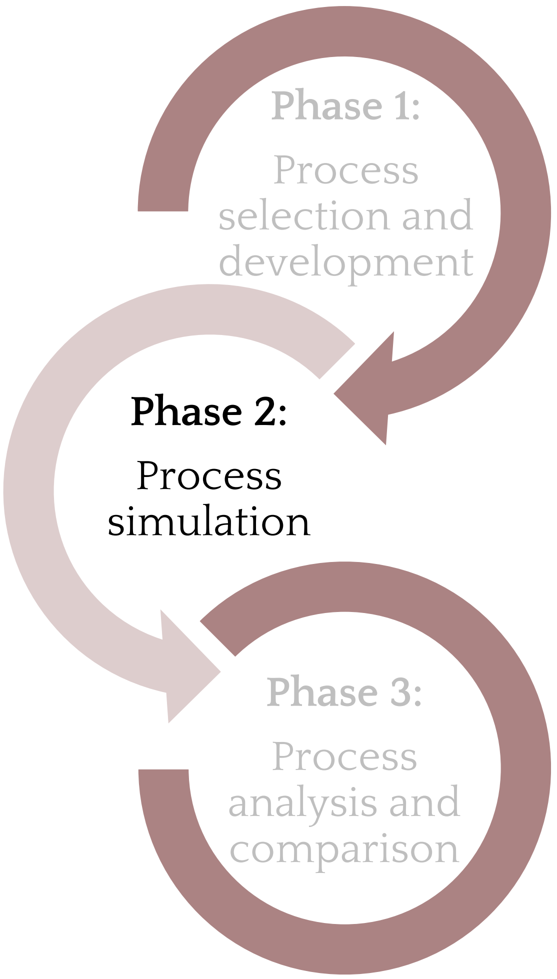
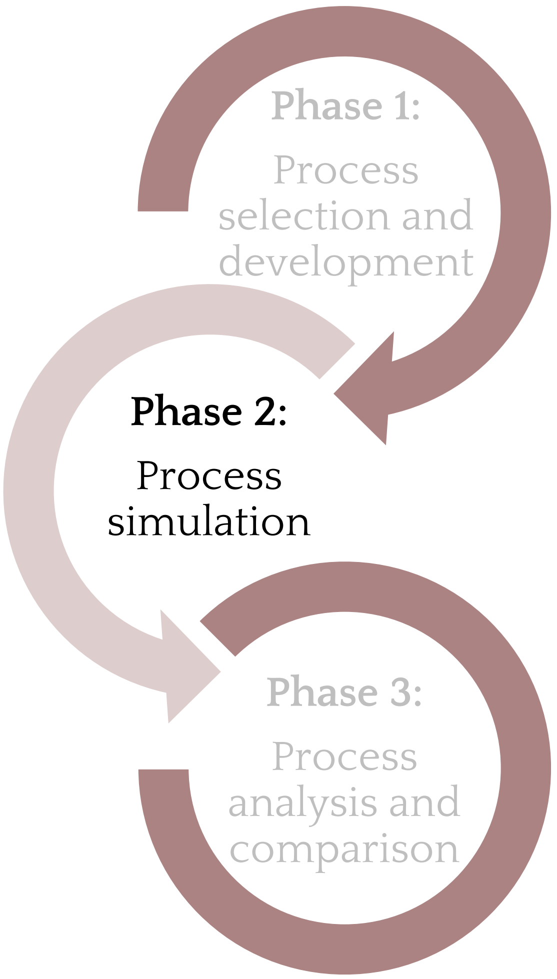


Table 3: Equipment sizing and description of the selected equipment

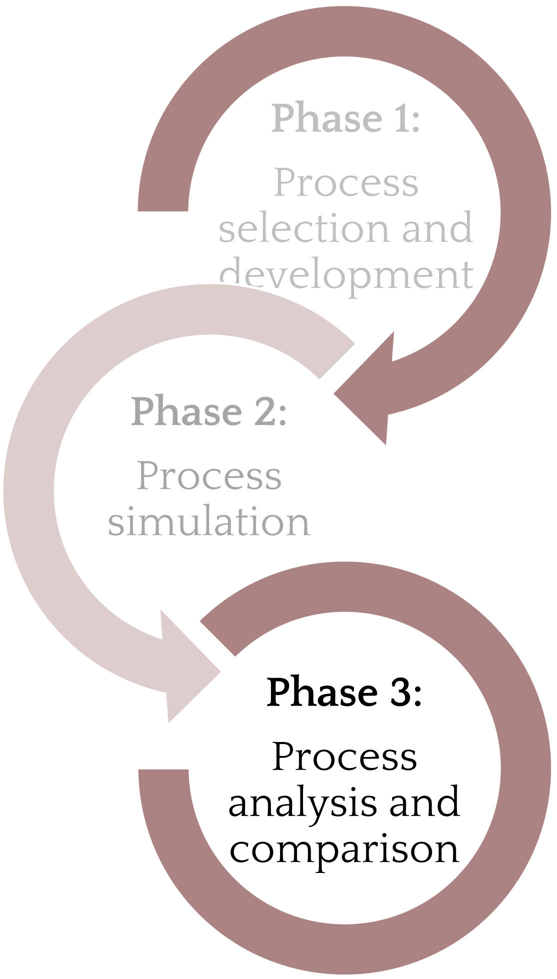
Equipment	Sizing	Description
Crusher machine	Capacity: 10 ton/h	- Suitable for large solids - Type: Roll crusher
Conversion reactor	Capacity: 10 m^3	- Material of construction: SS 316
Mixer	Capacity: 10 m^3	- Type: Open tank
Pump	Horsepower: 3 hp	- Improve the flow rate of the mixture - Simple and low maintenance cost - Suitable for 0.1 Pa.s of viscosities - Type: Centrifugal In-line flow pump - MOC: Cast steel
Heat exchanger	Area: 20 ft^2 Max pressure: 30 Mpa Temp: 200-600 ^oC	- Type: shell and tube, U-tube, Double pipe - MOC: Carbon steel for shell, SS for tube

Equipment Sizing and Description



Equipment	Sizing	Description
Splitter	Area: 200 ft^2	- Type: Rotary drum - MOC: SS 316
Component Splitter	Length: 2 – 5 m Dia: 0.5 – 1.5 m Area: 1 – 7.5 100 ft^2	- Type: Screen filter - Ease to use and low capital cost

Techno-Economic Analysis



Technical Aspect

Aspen Plus simulation

- Process simulation (biohydrogen production yield)
- Heat and mass balances, equipment selection and sizing

Economic Aspect

- TCI and AOC
- ROI, PBP and IRR
- Sensitivity Analysis

Environmental Aspect

Aspen Plus simulation

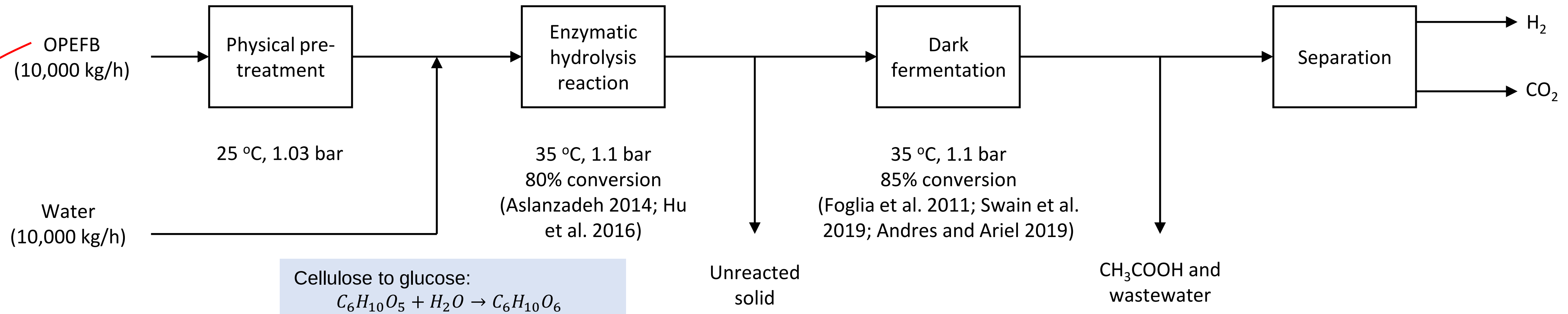
- Waste generation

Note: TCI – Total Capital Investment; AOC – Annual Operating Cost; ROI – Return on investment; PBP – Payback period; IRR – Internal Rate of Return

04

RESULTS AND DISCUSSION

Block Flow Diagram



Cellulose to glucose:

$$C_6H_{10}O_5 + H_2O \rightarrow C_6H_{10}O_6$$

Hemicellulose to xylose:

$$C_5H_8O_4 + H_2O \rightarrow C_5H_{10}O_5$$

Glucose to hydrogen:

$$C_6H_{10}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2$$

Xylose to hydrogen:

$$C_5H_{10}O_5 + 1.66H_2O \rightarrow 1.67CH_3COOH + 3.32CO_2 + 1.66H_2$$

Component	Chemical composition (wt %)
Cellulose	45.06
Hemicellulose	28.51
Lignin	12.39
Ash (CaO)	14.04

Figure 4: Overall block flow diagram for the biological process to convert the palm oil biomass waste (OPEFB) into biohydrogen

Process Flow Diagram

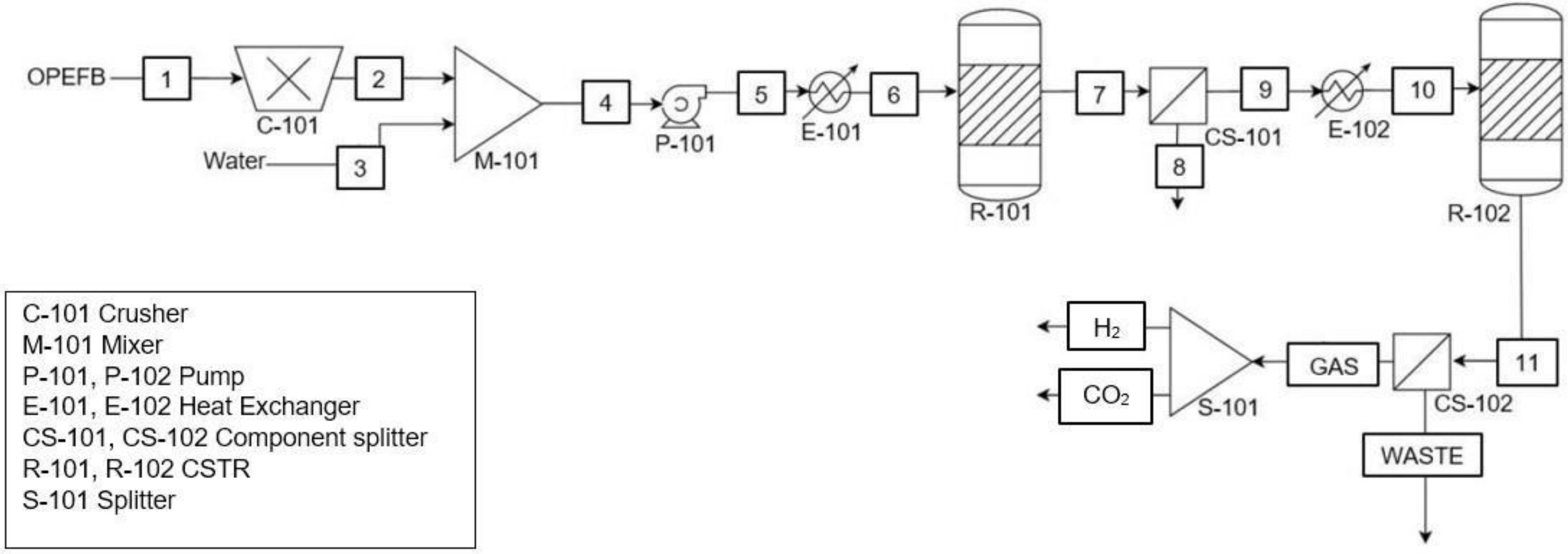


Figure 5: Process flow diagram for the biological process to convert the palm oil biomass waste (OPEFB) into biohydrogen

Aspen Simulation Flowsheet

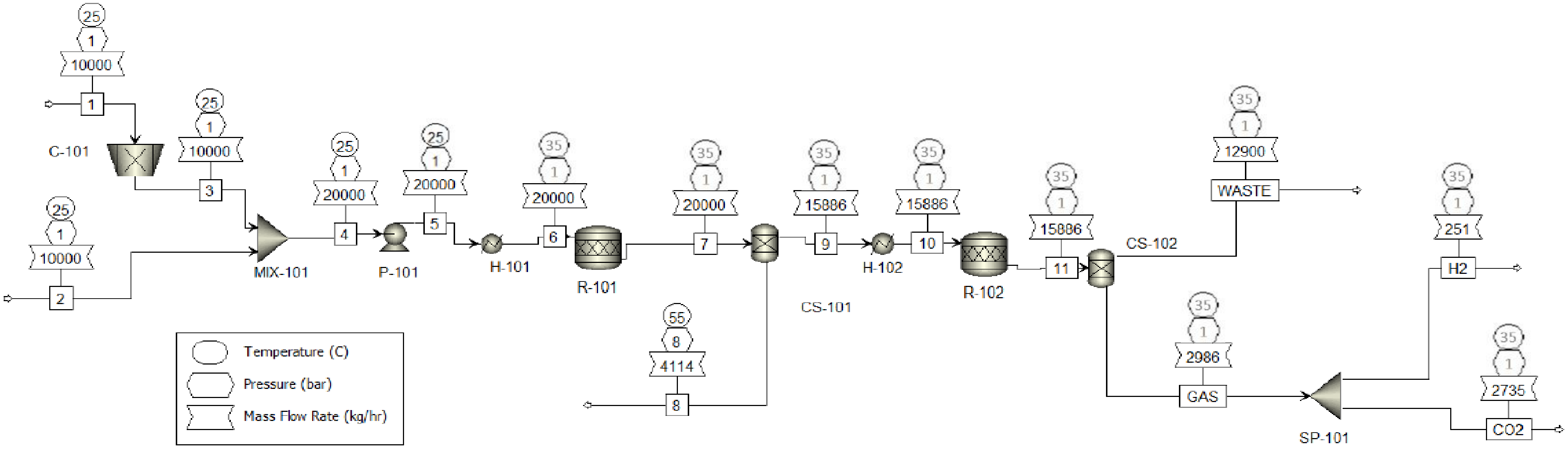


Figure 6: Aspen simulation flowsheet (flow diagram) for the biological process to convert the palm oil biomass waste (OPEFB) into biohydrogen

Technical Analysis

Basis: 10,000 kg/h OPEFB

Main Simulation Results

Table 4: Simulation inputs and outputs

Input	Flow rate	
	(kg/h)	(kmol/h)
Feedstock		
• OPEFB	10,000.00	84.5216
Others		
• Water	10,000.00	555.0840

Output	Flow rate	
	(kg/h)	(kmol/h)
Main product		
• **H_2**	**250.59**	**124.31**
By-products		
• CO_2	2,735.38	62.14
• Acetic acid	3,741.31	62.30

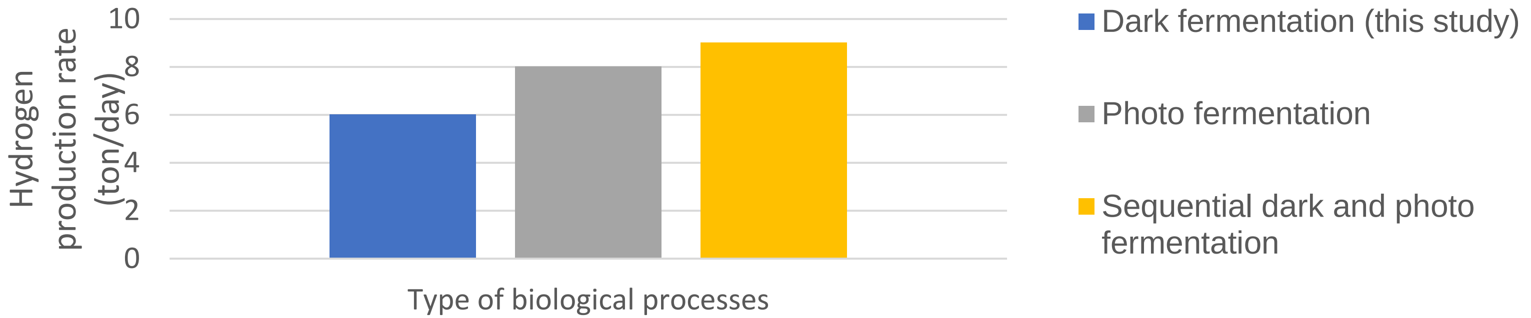
Technical Comparison

Optimal temperatures between 25-35 °C (biological process), CSTR avoid dead zones, lower hydrogen production due to absence of additional microorganisms to aid the fermentation and different pre-treatment used

Table 5: Comparison of the simulation outputs with those from literatures

Processes	Feedstock	Hydrogen production rate (ton H_2/day)	Additional microorganism	Pre-treatments	Number of units used	Type of reactor	Operating condition	References
Dark fermentation	**OPEFB**	**6.014**	**-**	• **Physical** • **Enzymatic Hydrolysis**	**10**	**CSTR**	**25 - 35°C**	**This study**
Dark fermentation	Coffee Cut-Stems	139	*T. thermosaccharolyticum*	• Acid Hydrolysis • Enzymatic Hydrolysis	12	CSTR	70°C	(García 2018)
Solid state and Dark fermentation	Food waste	117.42	*A. awamori* and *A. oryzae*	• Physical • Enzymatic Hydrolysis	21	CSTR	55°C, 70°C, N_2, $NaHCO_3$, H_2SO_4	(Han et al. 2016)
Steam reforming	Methane	239.5	-	-	13	Reformer and gas shift reactor	800 ° C-900 ° C, 15 bar- 30 bar, catalyst	(Aya et al. 2020)
Microbial electrolysis cell (MEC)	Waste water	0.7023	*Pseudomonas aeruginosa*	-	3	electrodes and vessel	25 ° C, pH 7, phosphate	(Meda 2015)

Technical Comparison



Lower hydrogen production in this study – different materials used, and different process

Figure 7: Hydrogen production rate from experiment data through different biological processes

Table 6: Hydrogen production rate from different processes in experiment-based

Biological processes	Feedstock	Photo Bacteria	Dark bacteria	References
Dark fermentation	**OPEFB**	**-**	**-**	**This study**
Photo fermentation	Corn stover	HAU-M1	-	(Lu et al. 2017)
Sequential dark and photo fermentation	Corn stover	HAU-M1	*Enterobacter Aerogenes*	(Lu et al. 2017)

Economic Analysis

Economic Analysis

1. Total Equipment Cost

2. Total Capital Investment (TCI)

3. Annual Operation Cost (AOC)

4. Annual Profitability Analysis

5. Hydrogen Production Cost

Table 7: Total equipment cost

Equipment	Price (USD)	Quantity	Price (USD)
reactor	8500	2	17000
mixer/agitated tank	6000	1	6000
heat exchanger	800	2	1600
pump	1000	1	1000
splitter	5000	1	5000
component splitter	3000	2	6000
crusher	4500	1	4500
storage tank	2000	1	2000
Total equipment cost (USD)			43100
Total equipment cost (MYR)			179296

Table 8: Annual operating cost

	Component	Price per unit (MYR)	Amount required per year	Cost (MYR)
Raw material	OPEFB	50 average RM/ton	87600	4380280.30
Utilities	Process water	4.48 RM/1000litre	87600000	392448
	Electricity	0.3945 RM/kwh	100000	39450
Extra	Maintenance	2% of FCC	-	5378.88
	Labour	17700 RM/labour	8	141600
	Insurance	1% of FCC	-	2689.44
Annual Operating Cost (AOC) (MYR)				4961846.60

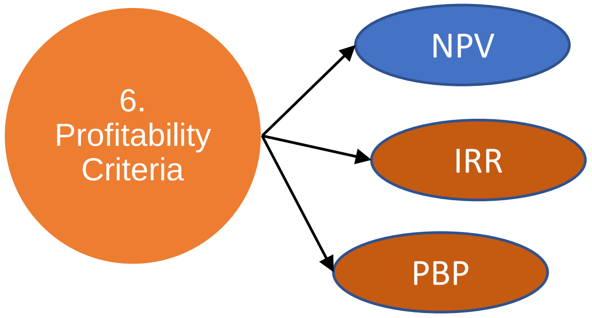
Economic parameters	Justification/ Formula
Fixed Capital Cost (FCC)	Plant cost + equipment cost (Lam et al. 2013)
Total Capital Investment (TCI)	FCC + WCC + land cost (Han et al. 2016; Fang et al. 2012)
Plant cost	50% of equipment cost (Han et al. 2016)
Working Capital Cost (WCC)	6.5% of FCC (Han et al. 2016)
Land cost	Assumed government support
Annual Operation Cost (AOC)	Total cost of raw material, utilities, waste and extra
Hydrogen production cost	$\frac{Cost\ of\ Capital + Utilities + Raw\ material + Extra}{Annual\ Hydrogen\ production}$

Table 9: Annual profitability

Component	Price	Quantity	Cost (MYR)
Hydrogen	USD 2.7/kg	2195155.3 kg	24655983.88/year
Annual Revenue	-	-	24655983.88/year
AOC	-	-	4961846.60/year
Annual profitability	-	-	14770603/year

General hydrogen price= USD 2.7/kg (Lam et al. 2013)

Economic Analysis



Note:
NPV – Net present value
IRR – Internal rate of return
PBP – Payback period

Net present value (NPV): Derived from cost of capital required to invest. t is time of cash flow, Rt is the net cash flow at time t, i is discount rate (Han et al., 2012)

$$NPV = \frac{R_t}{(1+i)^t}$$

Table 10: Net present value

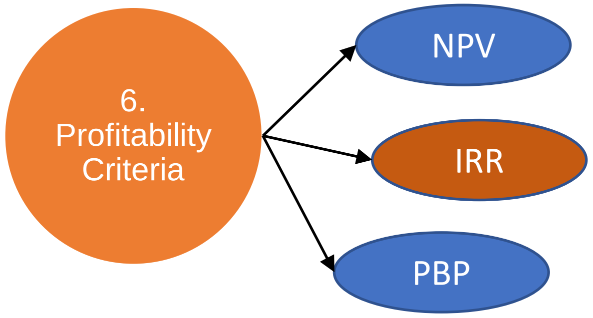
	Discount rate	0	0.05	0.1	0.15	0.2	0.25	0.3
year	cash flow	present value	present value	present value	present value	present value	present value	present value
0	0	0	0	0	0	0	0	0
1	-286425.36	-286425.36	-272786.0571	-260386.6909	-249065.5304	-238687.8	-229140.288	-220327.2
2	-186425.36	-186425.36	-169093.2971	-154070.5455	-140964.3554	-129462.0556	-119312.2304	-110310.8639
3	-86425.36	-86425.36	-74657.47543	-64932.65214	-56826.07709	-50014.67593	-44249.78432	-39337.89713
4	13574.64	13574.64	11167.88992	9271.661772	7761.344478	6546.412037	5560.172544	4752.858793
5	113574.64	113574.64	88988.70229	70520.91573	56466.66873	45643.10057	37216.13804	30588.95266
6	213574.64	213574.64	159372.6847	120557.3164	92334.21066	71525.71481	55987.31043	44247.58469
7	313574.64	313574.64	222851.6423	160913.3722	117884.322	87512.92706	65761.36834	49973.23522
8	413574.64	413574.64	279923.5955	192935.6218	135198.2834	96184.24315	69386.31067	50699.89757
9	513574.64	513574.64	331054.7921	217805.7817	145989.9659	99534.20591	68930.82134	48429.88075
10	613574.64	613574.64	376681.6035	236559.585	151666.2671	99095.72988	65882.07531	44507.56945
	total present value	1635746.4	953504.0806	529174.3661	260445.0993	87877.80193	-23978.10605	-96775.98191
	NPV function	RM1,635,746.40	RM953,504.08	RM529,174.37	RM260,445.10	RM87,877.80	-23978.10605	-96775.98191

Service year= 10 years

Assumed to be add RM 100,000 in every year (Han et al. 2016)

Following the NPV formula to find all the present value based on the year and discount rate (0 – 30%)

Economic Analysis



Note:
NPV – Net present value
IRR – Internal rate of return
PBP – Payback period

Payback period (PBP):
- Determined by counting the number of years the business takes to recover the funds invest. From the general rules, most medium businesses' payback period is between 4-6 years.

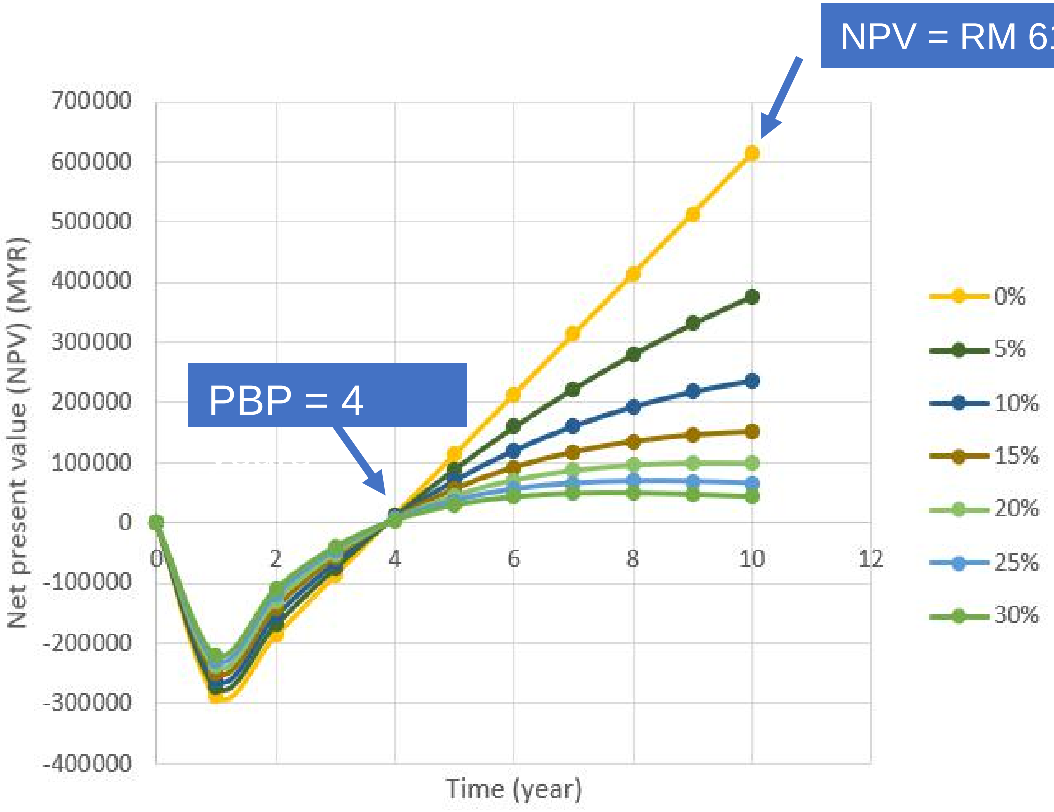


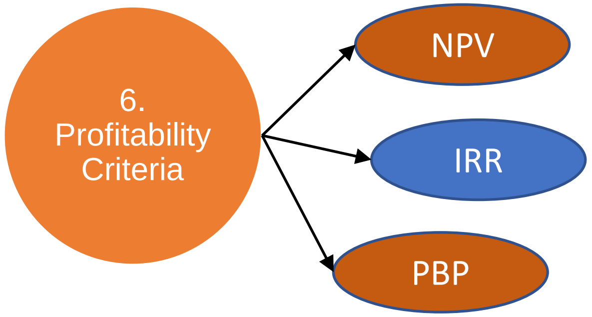
Figure 8: Net present value (NPV) of hydrogen production via dark fermentation at different discount rates

Discount rate from **30% to 0%** (Han et al. 2016)

Plant life assumed to be **10 years** (Fang et al. 2014)

Plant was **profitable** with a lower discount rate

Economic Analysis



Internal rate of return (IRR):

- Get IRR when NPV equal to 0.

- Analysed the degree of profitability of the plant. An ideal case is within the rate of 18% or above. However, in real estate investment, IRR always related to the capital cost, if the IRR was lower than the percentage of capital cost, then the investment is not profitable. As a result, the hydrogen production plant considered profitable as a short period with low IRR is acceptable based on the rule of thumb.

Table 11: Internal rate of return

discount	NPV at 0%
0	1635746.4
0.05	RM953,504.08
0.1	RM529,174.37
0.15	RM260,445.10
0.2	RM87,877.80
0.25	-RM23,978.11
0.3	-RM96,775.98

The plant is not profitable in these discount rate

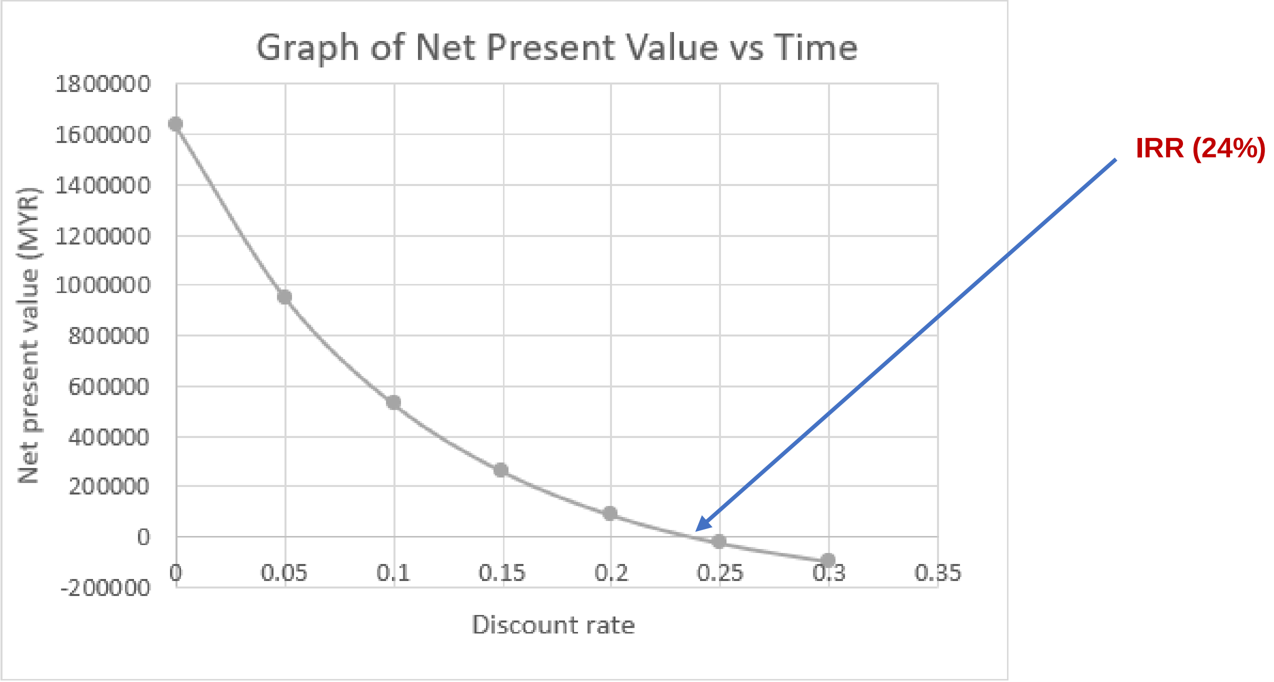


Figure 9: Internal rate of return

Economic Analysis

7.
Sensitivity
Analysis

Sensitivity analysis:
- Evaluate the **effects of dependent variable** if the independent variables are changing with certain %. The **independent variables are tax rate, total production cost and total annual revenue**, whereas the **dependent variable** is **NPV**.

Table 12: Economic parameters for Sensitivity Analysis

Component	Value
Total production cost (sum of TCI and AOC)	RM 5,248,272
TCI	RM 286,425
AOC	RM 4,961,847
Tax rate	25% (Malaysia Government 2021)
Service year	10
Annual Hydrogen Production cost	RM 24,655,983.88

Table 13: Tax rate for sensitivity analysis

Percentage range	Tax	NPV
-15%	0.2125	2225396.63
-10%	0.225	1976583.44
-5%	0.2375	1756960.95
0%	0.25	1562915.4
5%	0.2625	1391305.47
10%	0.275	1239397.16
15%	0.2875	1104808.04

- Example sensitivity analysis for tax rate:

0.25 × (1+15%)

((Annual Hydrogen production cost – Total Production cost) × (1-0.2875))/(1+0.2875)^(Service year))

Economic Analysis

7. Sensitivity Analysis

Sensitivity analysis:
- Evaluate the **effects of dependent variable** if the independent variables are changing with certain %. The independent variables are tax rate, total production cost and total annual revenue, whereas the dependent variable is NPV.

Table 14: Sensitivity slopes

Component	Sensitivity slopes
Revenue (hydrogen production)	2E+06x + 2E+06
Tax	-4E+06x + 2E+06
Total production cost	-422647x + 2E+06

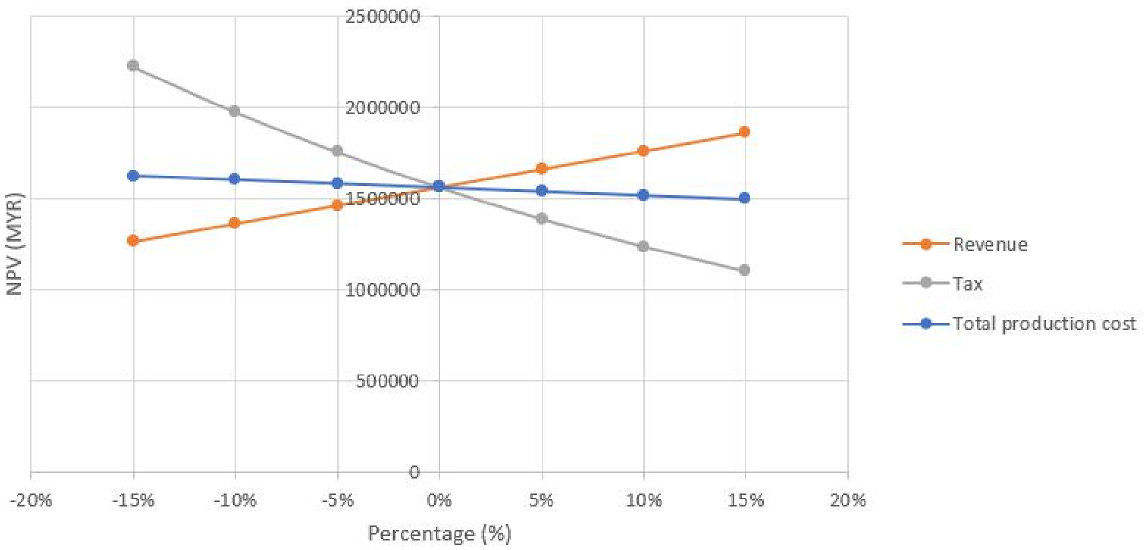


Figure 9: Sensitivity analysis of hydrogen production via dark fermentation from OPEFB

Malaysia tax rate: 25% in 2021 (Malaysia Corporate Tax Rate 2021)

Tax rate was the **major influence** compared to the total production cost of the plant as gradient is larger.

Sensitivity slope of hydrogen production was positive (profitable)

Economic Analysis

7.
Sensitivity
Analysis

Table 15: Comparison of economic analysis results with those from other literatures

Biological processes	Feedstock	Plant lifetime (years)	PB period (years)	IRR (%)	Revenue from hydrogen (USD)	References
Dark fermentation	Food waste	10	5.8	27.07	146,473.60	(Fang et al. 2016)
Dark fermentation	Bread waste	10	3	22	639,920.00	(Hu et al. 2016)
Dark fermentation	**OPEFB**	**10**	**4**	**24**	**525,156.77**	**This study**

IRR - Internal rate of return

- The PB period and IRR of this study is close to other literatures.
- The shorter payback period due to high revenue from hydrogen (Hu et al. 2016).
- From the rule of thumb in IRR, a short payback period with low IRR.

Summary for Economic Analysis

Table 16: Summary for the economic analysis

Economic parameters	Justification/ Formula	Amount (RM)
Total Equipment cost	10 units (Made-in-China 2021)	**179,296.00**
Fixed Capital Cost (FCC)	Plant cost + equipment cost (Lam et al. 2013)	**268,944.00**
Total Capital Investment (TCI)	FCC + WCC + land cost (Han et al. 2016; Fang et al. 2012)	**286,425.36**
Plant cost	50% of equipment cost (Han et al. 2016)	**89,648.00**
Working Capital Cost (WCC)	6.5% of FCC (Han et al. 2016)	**17,481.36**
Land cost	Assumed government support (Lam et al. 2013)	**-**
Annual Operation Cost (AOC)	Total cost of raw material, utilities, waste and extra	**4,961,846.60**
Hydrogen production cost	$\frac{Cost\ of\ Capital + Utilities + Raw\ material + Extra}{Annual\ Hydrogen\ production}$	**RM 9.46/kg or USD 2.27/kg**
Annual hydrogen production	365 batches per year	**2,195,155.3 kg/year**
Annual Revenue of hydrogen	General hydrogen price × Annual hydrogen production	**RM 24,655,983.88 /year**
Annual Profitability of hydrogen plant	Annual Revenue - AOC - Tax	**RM 14,770,603/year**

Comparison of Economic Aspects

The hydrogen production cost of this study is the lowest due to different pre-treatments and number of equipment used.

Table 17: Pre-treatment of dark fermentation process from different feedstock

Feedstock	Pre-treatments	References
OPEFB	**- Physical - Enzymatic Hydrolysis**	**This study**
Pinus Patula	- Mild-acid Hydrolysis (Sulfuric acid) - Enzymatic Hydrolysis	(Camilo 2018)
Coffee Cut-Stems	- Mild-acid Hydrolysis (Sulfuric acid) - Enzymatic Hydrolysis	(Garcia 2018)

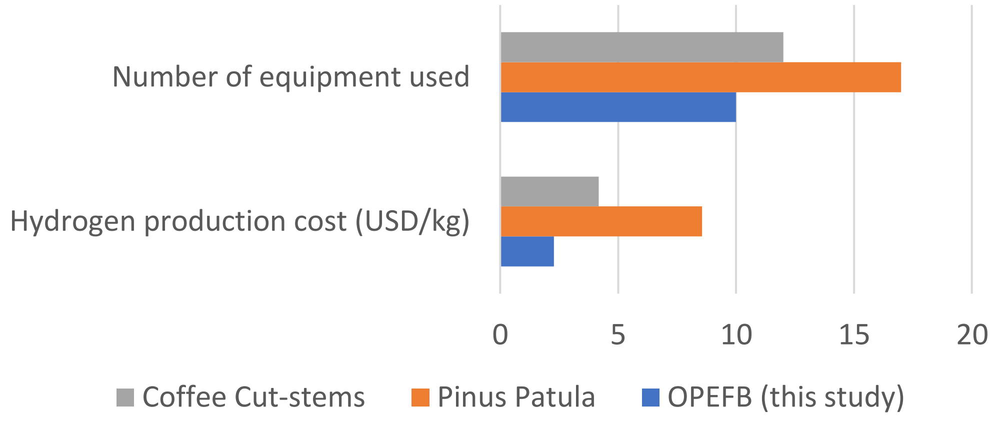


Figure 10: Hydrogen production cost from different feedstock (lignocellulosic waste) through dark fermentation process

Table 18: Hydrogen production cost from different processes

Type of Process	Processes	Unit Hydrogen Production price (USD/kg)	References
Thermochemical	Steam methane reforming	1.8	(Hatech et al. 2013)
Electrolysis	Water electrolysis	5 – 6	(Yasin et al. 2013)
Biological	**Dark fermentation from OPEFB**	**2.27**	**This study**
	Photo fermentation	2.83	(Nikolaidis 2017)
	Bio photolysis of water	4.15 – 7.24	(GeethaKannan 2015)

The hydrogen production price from thermochemical is the cheapest due to low feedstock and operating costs (Methane from natural gas is only USD 0.3/kg for large scale production) (Acar et al. 2016).

Comparison of Environmental Aspects

Output	Flow rate	
	(kg/h)	(kmol/h)
Main product		
• H_2	250.59	124.31
By-products		
• CO_2	2,735.38	62.14
• Acetic acid	3,741.31	62.30

Table 19: Carbon dioxide emission rate from different processes

Processes	Type of Processes	Feedstock	Carbon dioxide emission rate	References
Biological	**Dark fermentation**	**OPEFB**	**10.9 kg CO_2/kg H_2**	**This study**
	Solid state and dark fermentation	Food waste	1.5 kg CO_2/kg H_2 (after purification)	(Han et al. 2016)
Thermochemical	Steam reforming	Methane	7.05 kg CO_2/kg H_2	(Acar et al. 2018)
Electrolysis	Alkaline water electrolysis	Alkaline solution and water	-	(Kumar et al 2019)

Carbon dioxide emission
- Carbon dioxide capture and storage (CCS) can capture 90% of carbon dioxide gas before released to atmosphere (Peter 2015)
- Convert carbon dioxide into economically valuable and usable material (carbon-based products: ethanol, ethylene, methane can be produced from electrochemical carbon dioxide conversion)(Rackley 2017)
- Purification system (low-pressure gas tank, compressor, an activated carbon filter, desiccator and compression refrigerator)

Acetic acid
- According to Australia Government (2016), acetic acid does not harmful to human health, but it might cause environmental effect if the concentration is high and directly discharge into the sea.
- Separation from other waste using high energy consuming red processes (absorption, flash distillation, drying)(Das et al. 2021).
- Desired acetic acid was mixed with distillated water with ratio 1:10 to lower the concentration.
- Convert acetic acid into consumer products (vinegar, household detergents, sanitation products, paint removers) (Chant 2017)

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CONCLUSIONS AND RECOMMENDATION

Conclusions

Objectives

1 To compare and find a **practical biological process** to **produce biohydrogen** from **palm oil biomass wastes** on a larger commercial scale and develop the process description.

2 To **simulate the biological process** of biohydrogen production from palm oil biomass waste and perform a **techno-economic** analysis.

3 To **compare the analysis results** (in terms of the **technical**, **economic**, and **environmental** aspects) from this study with those from the literature.

Conclusions

- ✓ Dark fermentation is a **practical way** to produce biohydrogen from palm oil biomass waste (OPEFB)
- ✓ Dark fermentation offers **much simpler process**, and capable of producing biohydrogen in relatively high rates

- ✓ **Hydrogen production rate**: **251 kg/hr**; **Carbon dioxide** emission rate: 2735 kg/hr; **acetic acid** production rate: 3741 kg/hr
- ✓ Hydrogen production from OPEFB using dark fermentation is **profitable**, with a **payback period of 4 years**, and **internal rate of return of 24%**

- ✓ **Low hydrogen production rate** due to absence of additional microorganisms
- ✓ **Low hydrogen production price** due to **less number of equipment** and **different pre-treatment** used
- ✓ **High carbon dioxide emission** due to **high carbon content** of feedstock.

Recommendations and Future Research

Objectives

1 To compare and find a **practical biological process** to **produce biohydrogen** from **palm oil biomass wastes** on a larger commercial scale and develop the process description.

2 To **simulate the biological process** of biohydrogen production from palm oil biomass waste and perform a **techno-economic** analysis.

3 To **compare the analysis results** (in terms of the **technical**, **economic**, and **environmental** aspects) from this study with those from the literature.

Recommendation to improve the outcomes (for future research)

- ✓ **Refine** and **optimize** the dark fermentation process
- ✓ Get the **latest information** and the **kinetics data** for more accurate description of process
- ✓ Use **actual case/case study/ data** from **industry** for more accurate process description

- ✓ Use **latest version** of the software (**Aspen Plus v14**) to simulate the process
- ✓ Use **Heat Exchanger Network (HEN)** to minimize utility consumption
- ✓ Use **Aspen Process Economic Analyzer v14** to improve the reliability and accuracy of the calculations
- ✓ Perform **different scenario analysis** (**base case, best case, worst case**) using different prices of the biohydrogen
- ✓ **Extend the lifespan** of the plan from 10 years to 25-30 years

- ✓ Need to **compare with latest studies** especially those focusing on similar materials, or process
- ✓ Perform a **more detailed environmental analysis** covering the global warming and ozone depletion potential.
- ✓ Implement **recycling** to reduce the raw material cost
- ✓ **Treat wastewater** for re-utilizing some of the water

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Q & A