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Life Cycle Assessment on Methanol, Dimethyl Ether and Formaldehyde Production for Sustainable Carbon Dioxide Utilization Options

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Abstract—**The high risk of climate change impacts is a global concern due to Global Warming Potential (GWP) and greenhouse gas emission. Carbon Capture and Utilization (CCU) is a way to reduce GWP and also produce valuable products from CO_2. This research conducted Life Cycle Assessment (LCA) of CO_2 utilization for methanol, Dimethyl Ether (DME), and formaldehyde production from CO_2 and identified a product that efficiently utilized CO_2, providing valuable benefits while minimizing the overall environmental impacts. The research consisted of two parts: a model simulation of production processes and an environmental impact assessment. Model simulation covered the preparation of raw materials CO_2 and hydrogen, mixing, reaction, separation of gases, and absorption, with the last stage being distillation to purify the products. All data were analyzed using a model of the processes in the Aspen Plus V12 software. After that, the mass balance and net energy were employed for the environmental impact assessment using LCA based on a functional unit of 1,000 kg CO_2 feedstock and gate-to-gate approach. The results appeared that formaldehyde created the highest impacts, while DME has the lowest for all five impacts based on the same functional unit. It was also found that the impacts were mainly caused from the source of energy used in the process, which was produced from non-renewable energy source in Thailand. It can be concluded that CCU has the potential to help achieve net-zero targets and carbon neutrality, but the vital part is the energy source that should be from renewable energy.**

Keywords—**carbon dioxide utilization, methanol, dimethyl ether, formaldehyde, process simulation, life cycle assessment**

I. INTRODUCTION

Global Warming Potential (GWP) is becoming more severe, leading to widespread environmental impacts, with the main cause being the Greenhouse Gas (GHG) effect. CO_2 is a major source of the GHG effect. At present, all countries are seeking to develop technologies to reduce CO_2 emissions, mitigate the root cause of GWP, and remediate the environmental impacts. Recently, the record of CO_2 concentration has reached a high in the earth's atmosphere and its concentration is increasing annually. According to the United States Government Accountability Office (GAO) report in 2022, the average 2021 CO_2 concentration was 12.4 percent higher than in 2000. Carbon Capture, Utilization, and Storage (CCUS) is a beneficial technology being explored to obtain a valuable product from CO_2 emissions. CCUS technology involves two main steps: Carbon Capture and Storage (CCS), which focuses on capturing and storing CO_2, while the second step involves either storing or utilizing the captured CO_2, called Carbon Capture And Utilization (CCU) [1]. In addition, CCUS can be applied to improve the circular economy and sustainable development because the waste CO_2 can substitute for existing CO_2 as a raw material and be recycled to use as feedstock for producing a valuable product [2]. The CO_2 can be converted into valuable products, such as methanol, to capture the highest possible value. Methanol is among the chemical commodities imported in Thailand, and it is the precursor for producing other chemicals, such as Dimethyl Ether (DME) and formaldehyde. DME is an eco-chemical compound and alternative fuel source being non-toxic, biodegradable, colorless, and non-corrosive, as well as not containing Particulate Matter (PM) and Sulfur Oxides (SOx) [3]. Likewise, Formaldehyde (FM) is an important chemical for many industries in the production and construction of building materials, textiles, sterilization products, plastics, and cosmetics [4]. Methanol production uses CO_2 as the main feedstock; however, it needs other chemicals and energy that create adverse environmental impacts during their production process. Furthermore, the DME and formaldehyde production processes use methanol as a main feedstock in addition to other chemicals and energy that can create environmental impacts [4–6]. Consequently, there is a need to assess the environmental impact of the production process. LCA is one of the best environmental performance tools that have been widely adopted for environmental impact assessment, based on the standardized approach specified in the ISO 14040 standards. LCA can analyze, compare, and evaluate the largest hotspot of environmental impact in every step of the production process [7]. CO_2 is currently being used or converted into valuable products which has over 230 million metric tons annually [1]. CCUS plays a critical role in reducing CO_2 levels in the atmosphere. CCUS can mitigate and temporarily store the CO_2 emission to the atmosphere, although electricity, hydrogen supply chain, and heavy metal contamination were the highest burdens of the CCU implementation process [8].

Many researchers analyzed the environmental burden of methanol and DME production processes, although FM from carbon utilization has not been many comprehensive studies. Most research assumed that electricity came from renewable sources and neglected the consumption of electricity from the country's electricity grid mix or non-renewable energy sources. The research would like to fill a

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gap in the environmental impact analysis of valuable products of CCUS technology by using the Thailand electricity grid mix. The current research aim was to identify a product that could efficiently utilize CO_2, providing valuable benefits while minimizing overall environmental impacts.

II. LITERATURE REVIEW

A. *Carbon Capture, Utilization and Storage (CCUS) Technologies*

The Carbon Capture and Storage (CCS) technology is characterized by the concentrated stream of CO_2 from fuel combustion and the implementation of point sources. The carbon capture categories are post-combustion, pre-combustion, oxyfuel combustion, and direct air capture. Post-combustion captured the CO_2 from the process flue stream after the combustion processes which has CO_2 concentration between 17% to 70%, and typical pressure about 1 bar. Pre-combustion is separated the CO_2 from syngas before the combustion which has CO_2 concentration between 15% to 60%, and typical pressure between 14 bar to 70 bar. Oxyfuel-combustion involved the use of pure oxygen (>95%) instead of air for combustion which has CO_2 concentration between 3% to 20%, and typical pressure about 1 bar. Direct air capture captured the CO_2 from the ambient air for CO_2 concentration up to 0.04% and typical pressure about 1 bar [9]. The carbon captured technologies are based on CO_2 separation such as absorption, adsorption, membranes, cryogenic distillation, calcium looping and chemical looping [10]. The carbon capture and utilization (CCU) converted the captured CO_2 from a product by using the conversion pathways such as mineral carbonation, hydrogenation, electrochemistry, co-polymerization, and microbial conversion [1]. Carbon capture, storage and utilization (CCUS) is ready for wider deployment in carbon emissions reduction pathways although its application is still challenging and limited due to constraints in the technology readiness level, economic feasibility, and commercial plant establishment. The captured CO_2 must have high purity and be readily available to the market for use in the industrial process. The captured CO_2 process should be applied to minimize environmental impacts and maximize the benefits and value of CO_2 [1]. Environmental impacts of methanol, DME, and formaldehyde based on CCUS technology.

Methanol and DME from CO_2 hydrogenation reduced the GHG emissions about 82–86% and reduced fossil fuel depletion by 82–91% compared to conventional petroleum-based fuels [4]. A methanol production process that used CO_2 as an energy input reduced the carbon emissions by 1.5 kgCO_2 per kilogram of methanol production [5]. Comparing the production of DME and methanol based on the same feedstock, the DME impacts were higher than for methanol. The largest environmental hotspot was the fuel production process of the DME process [8]. The significant environmental impacts of methanol, DME, and FM production were GWP, ecotoxicity, human non-carcinogenic toxicity and resource scarcity associated with major pollutants of production and raw material extraction processes such as SO_2, NOx, CO_2, CH_4, N_2O emissions and particulate matter [11, 12].

III. MATERIALS AND METHODS

The research was separated into two parts: 1) model simulation; and 2) environmental impact assessment of products. The model simulation used the Aspen Plus V12 software to measure the mass balance and molecular balance of the inputs and outputs in all steps of the methanol, DME, and formaldehyde production processes based on CO_2. Then, the data from modeling was used in the life cycle inventory (LCI) phase, with the evaluation of environmental impacts based on the LCA (gate-to-gate) approach and system boundaries, as shown in Fig. 1.

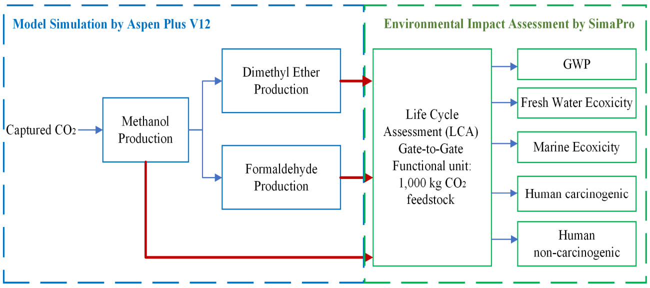

Fig. 1. System boundaries of methanol, dimethyl ether, and formaldehyde production from CO_2.

B. *Process Design and Modelling*

1) *Model of methanol production process from CO_2*

Fig. 2 shows the methanol production process from CO_2 that can be divided into:

- Raw materials preheat, where the main raw material (CO_2 gas) from an external source was heated 300ºC and pressurized to 50 bar.
- Reaction, with four reactions occurred in a plug flow reactor in Eqs. (1)–(4) [5]:

1) Reverse Water Gas Shift reaction

$$CO_2 + H_2 \leftrightarrow CO + H_2O \tag{1}$$

2) CO_2 Hydrogenation

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \tag{2}$$

3) Methanol Synthesis

$$CO + 2H_2 \rightarrow CH_3OH \tag{3}$$

4) Steam Methane Reforming

$$CO + 3H_2 \rightarrow CH_4 + H_2O \tag{4}$$

- Separation, where the light gases were separated in a two-phase separator from mixed with methanol, water and a tiny amount of CO_2. The light gases were recycled back into the production process.
- Distillation was the final step involving separation of the water from the methanol to achieve high purity methanol (up to 99%).

From this production process, light gases from the purge 1 and purge 2 steams entered the next combustion process, where they combusted with air at flow rates of 5,700 kmol/hr and 1,500 kmol/hr, respectively, in a stoichiometric reactor (RStoic) at 200°C and a pressure of 1 bar.

2) *Model of DME production process from methanol*

Fig. 3 shows the process of producing DME from methanol, beginning with the raw material preparation process. Methanol was mixed with the methanol obtained from recycle stream resulting in a mix of methane (CH_4), CO_2, carbon monoxide (CO), and water (H_2O). The gas temperature was increased using the heat exchanger (HX) and the heater (HT1) before entering the reaction process in a plug flow reactor (Rplug), where the following reaction occurred in Eq. (5):

$$2CH_3OH \rightarrow CH_3OCH_3 + H_2O \tag{5}$$

Acid zeolite catalyst was used to accelerate the reaction and then the temperature of the resulting products (DME, water, methanol) from the reactor (PFR) were reduced using a HX and a chiller. Next, the steams entered the distillation phase to separate the DME, methanol and water using the first distillation column. First, the DME was separated, and then the water and methanol were separated using the second distillation column. After that the methanol re-entered the recycle stream because a large volume of methanol mixed with water remained that was separated using the third distillation column to obtain purified methanol. The purified methanol could be reused in the recycling stream, completing the production process. Purified methanol was obtained as a co-product, with DME as the main product.

3) Model of formaldehyde production process from methanol

Fig. 4 shows the model of the formaldehyde production process from methanol using silver as a catalyst. First, the raw material preparation used methanol at a flow rate of 990 kmol/hr and air at a flow rate of 421.77 kmol/h. The feedstock stream temperature was adjusted to the desired level before entering the mixing process between the two raw materials. Next, the temperature of the materials was reduced before entering the reaction process in Rplug. In the reactor, the methanol and air were converted to formaldehyde gas at 200°C. Two reactions occurred in Eq Eqs. (6, 7):

$$CH_3OH + \frac{1}{2} O_2 \rightarrow CH_2O + H_2O \tag{6}$$

$$CH_3OH \rightarrow CH_2O + H_2 \tag{7}$$

The temperatures of the products from PFR were reduced using a chiller before entering the process to separate the hydrogen gas and nitrogen gas from methanol, water, and formaldehyde. In addition, the methanol was separated in a 2-phase separator. Then, the temperature was increased before entering the formaldehyde gas-absorbing process using another absorber, where the formaldehyde gas was converted into a formaldehyde solution. The solution entered the first distillation column (DST1) for the removal of the remaining methanol in the formaldehyde solution. Next, the solution entered the second distillation column for additional purification and removal of the remaining methanol to get the desired formaldehyde percentage. The final formaldehyde product had 60% purity. The model simulated the methanol obtained from the CO_2 off-gas stream being combusted in the RStoic reactor with the air at a flow rate of 1,200 kmol/hr, an operating temperature of 200°C, and a pressure of 1 bar.

C. Life Cycle Assessment of Product

The goal was to compare the environmental impacts of the methanol, DME, and formaldehyde production processes using the same functional CO_2 feedstock unit of 1,000 kg CO_2. The system boundary was restricted to the production process of methanol, DME, and formaldehyde that excluded the construction, distribution, transportation, and use of the feedstock. The main CO_2 feedstock was assumed to have come from an external facility. In the LCI phase of LCA, the mass balance and energy consumption data were obtained from the Aspen Plus software. For life cycle impact assessment, ReCiPe is a fast method for conducts life cycle impact assessment which can provide the global scale in line with the global nature of many products life cycle. Furthermore, the hierarchies perspective is based on scientific consensus and it regards the time frame and the reasonable or probable impact mechanisms [13]. The environmental impact assessment was analyzed using the ReCiPe 2016 v1.04 midpoint, hierarchical via SimaPro software v.9.1.1.1 and Ecoinvent 3.6 as database, with gate-to-gate approach.

IV. RESULT AND DISCUSSION

A. Model Simulation

Table 1 shows the materials balance for the methanal, DME, and formaldehyde production model in the model simulation using the Aspen plus v12 software.

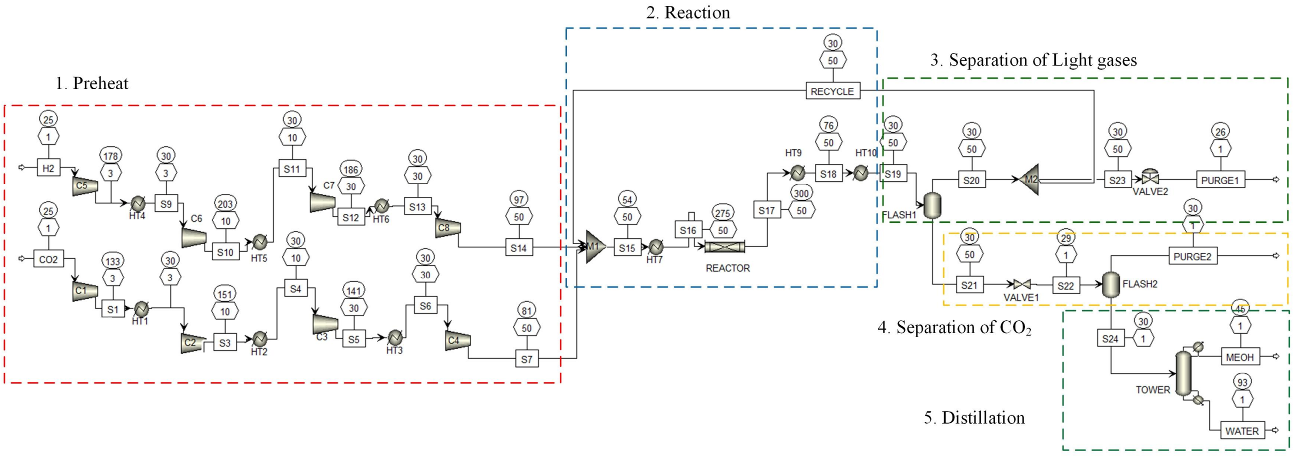

Fig. 2. Generalized model of methanol production proces from CO_2.

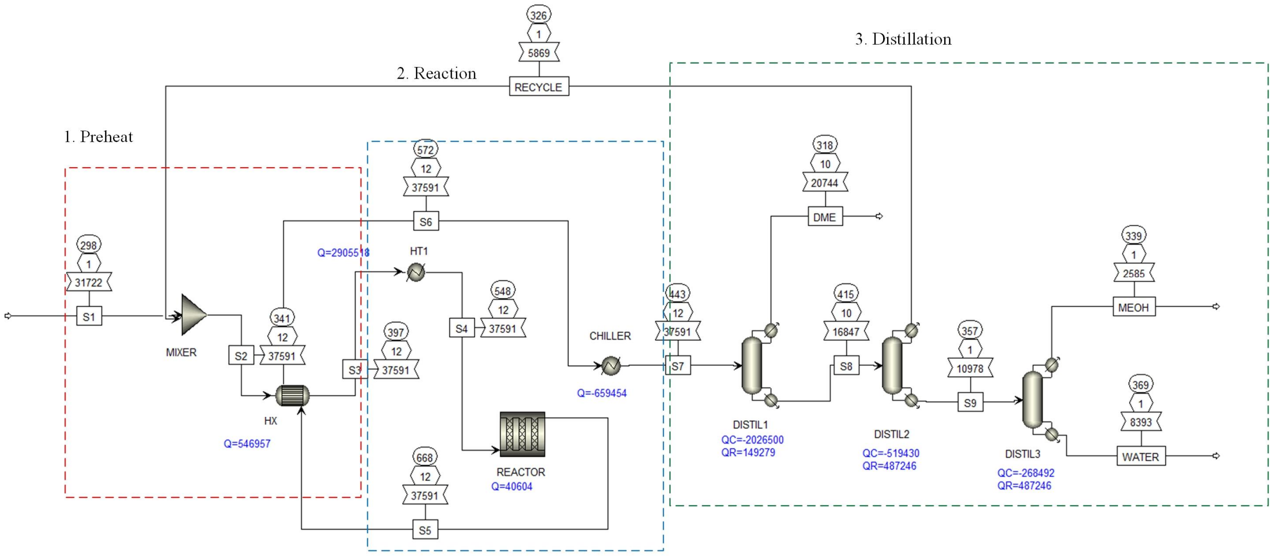

Fig. 3. Generalized model of production process of dimethyl ether from methanol.

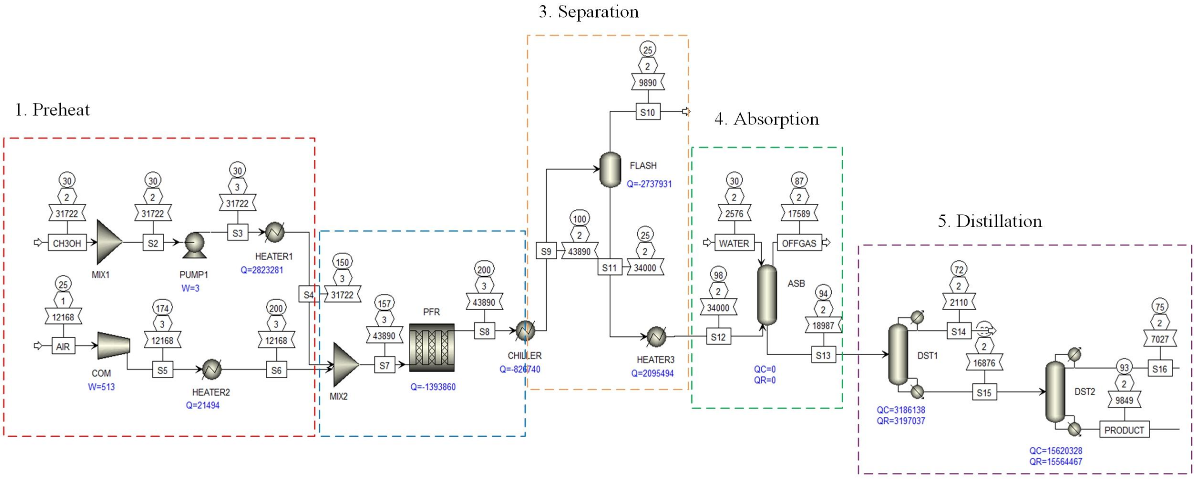

Fig. 4. Generalized model of formaldehyde production process from methanol.

Table 1. Materials balance for methanol, DME, and formaldehyde production from CO_2

Parameter		Methanol	DME	Formaldehyde
Temperature	ºC	45	44	93
Pressure	bar	1	10	1.5
Input				
CO_2	kg	1,000	1,000	1,000
Hydrogen	kg	145.23	142.86	143.86
Air	kg	605.81	3,307.28	3,304.82
Water		-	-	33.44
Electricity	kWh	1,416.61	1,554.61	3,528.35
Outputs (product/co-product)				
Methanol	kg	414.94	32.83	298.60
Dimethyl ether	kg	-	269.54	-
Formaldehyde	kg	-	-	77.76
Emissions				
Emission to Air				
CO_2	kg	402.49	404.31	416.80
Nitrogen	kg	1,639	1,641.51	2,107.31
Oxygen	kg	8.30	132.08	219.28
Hydrogen	Kg	-	-	3.90E-04
Water	kg	979.25	981.13	1,041.99
DME	kg	-	4.04E-07	-
Formaldehyde	kg	-	-	1.14E-20
Emission to Water				
Methane	kg	1.54E-31	1.55E-11	1.55E-31
CO_2	kg	9.36E-17	9.38E-18	9.38E-17
CO	kg	2.33E-34	2.34E-34	2.34E-34
Water	kg	244.81	350.40	246.5
Hydrogen	kg	2.66E-33	2.66E-33	2.66E-33
Methanol	kg	20.75	24.26	19.44
DME	kg	-	9.52E-15	-

B. Life Cycle Assessment of Methanol, DME and Formaldehyde

Table 2 shows that environmental impacts from methanol, DME and formaldehyde production process as same feedstock CO_2 1,000 kg for each product by gate-to-gate approach and the electricity was considered Thailand Electricity mix due to plant location in Thailand. The environmental impacts were focused on Freshwater ecotoxicity, Marine ecotoxicity, Human carcinogenic toxicity and Human non-carcinogenic toxicity caused by the highest impacts in normalization constants of ReCiPe 2016. Moreover, GWP is currently the highest global attention, the leading impacts and highest challenges in global environmental problems that is focused on this study followed by net zero emission 2050 [14].

Table 2. Life cycle Impact Assessment of methanol, DME and formaldehyde

Impact indicators	Unit	Methanol	DME	FM
Global warming potential	kg CO_2 eq	1,515	1,488	3,077
Freshwater ecotoxicity	kg 1,4-DCB	11	8	52
Marine ecotoxicity	kg 1,4-DCB	15	12	70
Human carcinogenic toxicity	kg 1,4-DCB	28	36	86
Human non-carcinogenic toxicity	kg 1,4-DCB	163	551	1,466

DCB: Dichlorobenzene

1) *Global warming potential*

Fig 5 shows that for the same functional unit of feedstock (1,000 kg CO_2), the formaldehyde production process had the highest impacts on GWP (3,344 $kgCO_2eq.$), followed by DME process (1,893 $kgCO_2eq.$), and methanol (1,797 $kgCO_2eq.$), respectively. However, the products and co-products from table 1 were also counted as benefit to be deducted from the GWP impact as shown in Fig 5. In case of methanol process, the main product (414.94 kg methanol) could be offset by 282 $kgCO_2eq$. For DME process, methanol (32.83 kg) and DME (269.54 kg) products could be offset for 405 $kgCO_2eq$. Finally, methanol (298.6 kg) and formaldehyde (77.76 kg) products could save 266 $kgCO_2eq.$ in the case of formaldehyde process. As the result, the total impacts on GWP for methanol, DME and formaldehyde process became 1,515 1,488 and 3,077 $kgCO_2eq.$ respectively, as shown in Fig. 5. This approach was also applied to all other LCA indicators in this work. The GWP from formaldehyde case mainly came from energy consumption in the production process of up to 2,567 $kgCO_2eq$ which was directly influenced by Thailand's electricity mix due to non-renewable energy's share of 77% in the total electricity mix [15].

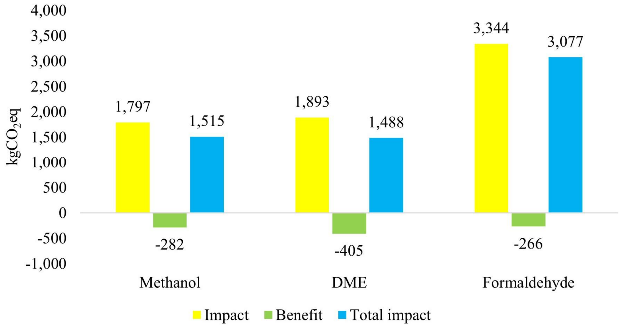

Fig. 5. Global warming potential of methanol, DME, and formaldehyde from 1000 kg CO_2 feedstock.

2) *Freshwater ecotoxicity*

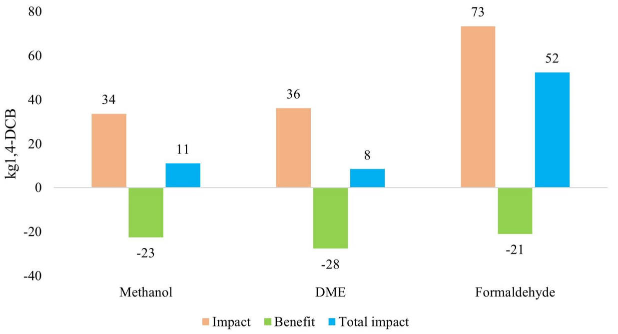

Fig. 6. Freshwater ecotoxicity of methanol, DME, and formaldehyde by CO_2 1000 kg.

In Fig. 6, formaldehyde was the leading product in terms of freshwater ecotoxicity, with a net impact of (52 kg1,4-DCB), followed by methanol (11 kg1,4-DCB), and (DME 8 kg1,4-DCB), respectively. The result illustrated that the utilize methanol from CO_2 reduced the impact 23 kg1,4-DCB for methanol, utilize DME and methanol from CO_2 could save 28 kg1,4-DCB for DME and utilize formaldehyde and methanol from CO_2 could offset 21 kg1,4-DCB for formaldehyde. Electricity was the main contributor to the freshwater ecotoxicity impact, accounting for 48% of the impact of methanol, 82% of DME, and 91% of FM, respectively. Moreover, the production processes of each product discharge water containing contaminants such as zinc, nickel, copper, and vanadium, which has led to toxicity in freshwater bodies.

3) *Marine ecotoxicity*

From Fig. 7, formaldehyde had the highest impact in the marine ecotoxicity, with a net impact of (70 kg1,4-DCB), followed by methanol (15 kg1,4-DCB), and DME (12 kg 1,4-DCB), respectively. The utilize methanol from CO_2 could offset 29 kg1,4-DCB for methanol, utilize DME and methanol from CO_2 could save 36 kg1,4-DCB for DME and utilize formaldehyde and methanol from CO_2 could offset 27 kg1,4-DCB for formaldehyde. The result indicated that electricity was the primary contributor to marine ecotoxicity, accounting for 48% of methanol, 47% of DME, and 71% of FM, respectively. The main contamination of methanol, DME, and FM production processes were zinc, nickel, copper, and vanadium, which was the main creator of marine ecotoxicity.

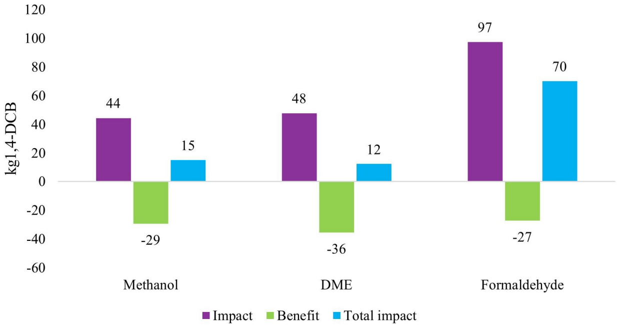

Fig. 7. Marine ecotoxicity of methanol, DME, and formaldehyde by CO_2 1000 kg.

4) *Human carcinogenic toxicity*

From Fig. 8, formaldehyde had the highest impact for human carcinogenic toxicity, producing 100 kg1,4-DCB, while utilizing methanol and formaldehyde from CO_2 could save 14 kg1,4-DCB that reduced the impact to 86 kg1,4-DCB. DME produced 48 kg1,4-DCB although utilize methanol and DME from CO_2 could offset 12 kg1,4-DCB, so that the net impact was 36 kg1,4-DCB, with methanol having the lowest impact of 44 kg1,4-DCB while utilize methanol from CO_2 could save 16 kg1,4-DCB that reduced the impact to 28 kg1,4-DCB.

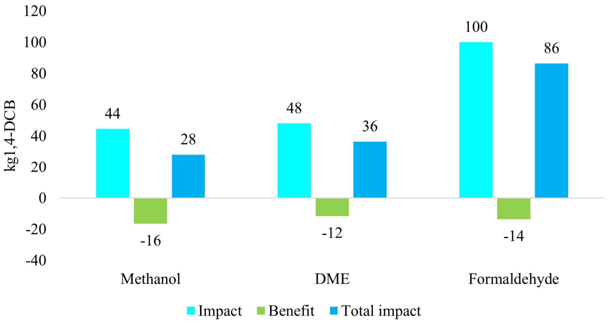

Fig. 8. Human carcinogenic toxicity of methanol, DME, and formaldehyde by CO_2 1000 kg.

5) *Human non-Carcinogenic Toxicity*

From Fig. 9, the net impact of formaldehyde was still the highest, being 2,074 kg1,4-DCB, while methanol and formaldehyde from CO_2 utilization saved 608 kg1,4-DCB, reducing the impact to 1,466 kg1,4-DCB. Likewise, DME produced 988 kg1,4-DCB although methanol and DME from CO_2 utilization could offset 437 kg1,4-DCB, reducing the impact to 551 kg1,4-DCB. Methanol production had the lowest impact of 914 kg1,4-DCB while utilize methanol from CO_2 could save 751 kg1,4-DCB, so that the net impact was 163 kg1,4-DCB. The impact of formaldehyde mainly came from the energy used in the production process.

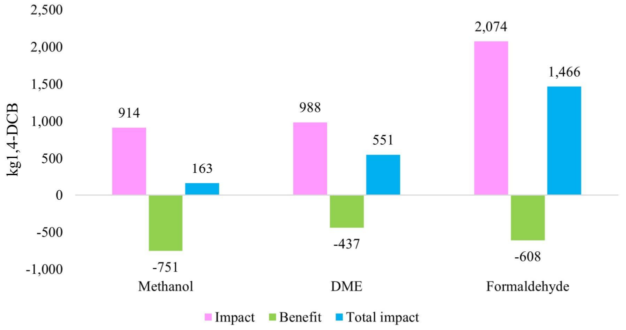

Fig. 9. Human non-carcinogenic toxicity of methanol, DME, and formaldehyde by CO_2 1000 kg.

C. Sensitivity Analysis of Global Warming Potential from Methanol, DME and Formaldehyde Production

The research considered ways to reduce the environmental impacts by focusing on emission reduction, GWP reduction, and CCU implementation based on the following sensitivity analyses:

1) Compare the GWP of methanol, DME, and formaldehyde based on just material consumption, neglecting energy consumption.
2) Compare the GWP of methanol, DME, and formaldehyde based on various percentage of renewable energy usage.

1) Compare global warming potential of methanol, DME, and formaldehyde based on just material consumption

From Fig. 10, formaldehyde produced 777 $kgCO_2eq.$ while utilize methanol and formaldehyde from CO_2 could offset 266 $kgCO_2eq.$ that reduce the GWP to 510 $kgCO_2eq.$ Methanol produced 766 $kgCO_2eq.$ although utilize methanol from CO_2 could save 282 $kgCO_2eq.$ that reduce GWP to 484 $kgCO_2eq.$ DME produced 762 $kgCO_2eq.$, while methanol and DME from CO_2 utilization could offset 405 $kgCO_2eq$ that reduce the GWP impact to 357 $kgCO_2eq.$ The GWP of formaldehyde came from hydrogen consumption (360 $kgCO_2eq.$), and GWP of methanol mainly came from hydrogen consumption (363 $kgCO_2eq.$).

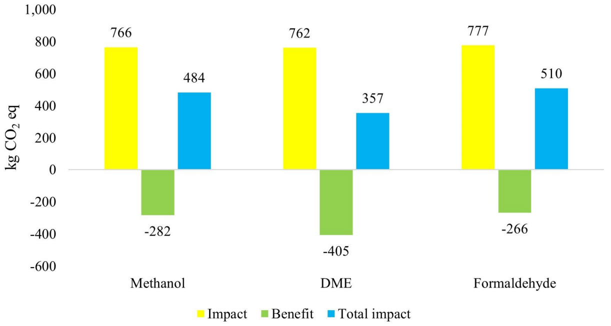

Fig. 10. Global warming potential of methanol, DME, and formaldehyde by CO_2 feedstock 1000 kg (consider just material consumption).

2) Compare global warming potential of methanol, DME, and formaldehyde by renewable energy usage percentage

A range in renewable energy percentages (10%, 20%, 30%, 40%, 50% and 100%) was assumed for the GWP evaluation process. Renewable energy at 10% represents 10% renewable energy (Electricity, biomass, at power plant, in the Ecoinvent database), with the balance of 90% coming from the Thailand country electricity mix. From Fig. 11 and Table 3, the renewable energy percentage dominated the GWP impact reduction process. These results confirmed that environmentally friendly and CCUS implementation should use renewable energy instead of non-renewable energy sources. Furthermore, the methanol utilized from CO_2 could offset the environmental impacts, indicating that CO_2 utilization was beneficial in environmental impact reduction and emission reduction pathways.

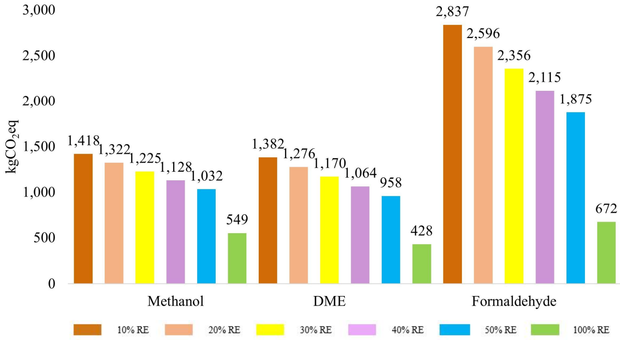

Fig. 11. Global warming potential of methanol, DME, and formaldehyde by CO_2 feedstock 1000 kg (Renewable energy percentage variable).

Table 3. Global warming potential of product based on variable renewable energy percentage for energy consumption (kg $CO_2eq.$/1,000 kg CO_2 feedstock)

FM	DME	Methanol	Renewable Energy %
2,837	1,382	1,418	10% RE[a] + 90% EM[b]
2,596	1,276	1,322	20% RE[a] + 80% electricity mix[b]
2,356	1,170	1,225	30% RE[a] + 70% electricity mix[b]
2,115	1,064	1,128	40% RE[a] + 60% electricity mix[b]
1,875	958	1,032	50% RE[a] + 50% electricity mix[b]
672	428	549	100% RE[a] + 0% electricity mix[b]

[a] = Renewable energy, [b] = Thailand country electricity mix

3) Environmental impacts compare between the current study and existing literature

The direct comparison on the LCA results with other works were slightly difficult according to the different LCA approaches, database used, simulation methods, and the functional units. Mahabir *et al.* [11] investigated the mega-methanol production from carbon utilization which used their electricity sources, a functional unit of 1 ton methanol production, cradle-to-gate approach, and SimaPro, ReCiPe 2016 (H). Puhar *et al.* [12] determined the environmental impacts of formaldehyde production via methanol stream reforming by using OpenLCA software which is cradle-to-gate approach and functional unit as production of 1 kg product. Rigamonti *et al.* [16] considered the functional unit as 1,000 kg treatment of process gases, environmental impact was evaluated by the Environmental Footprint (EF) method. To ensure comparability, all results were standardized to the same functional unit for each study, except for variations in the LCA approach and simulation method. Table 4 shows the environmental impact comparison between the existing literature and the current study.

Table 4. Global warming potential, Freshwater and marine water ecotoxicity, human carcinogenic and non-carcinogenic toxicity comparison between the current study and existing literature

	Mahabir *et al.* [1]	**Puhar *et al.* [12]**	**Rigamonti & Brivio [16]**	**Base case**	**100% RE**
Global warming potential (GWP) (kgCO₂eq/kg product)					
Methanol	0.28		0.49	3.65	1.32
DME				5.52	1.59
Formaldehyde		1.37		39.58	8.64
Freshwater ecotoxicity (kg1,4-DCB/kg product)					
Methanol			-0.19	0.001	-0.0002
DME				0.002	-0.0002
Formaldehyde				0.020	-0.0008
Marine water ecotoxicity (kg1,4-DCB/kg product)					
Methanol			-0.01	0.036	-0.0493
DME				0.045	-0.0993
Formaldehyde				0.901	-0.2364
Human carcinogenic toxicity (kg1,4-DCB/kg product)					
Methanol			-2.68E-09	0.068	-0.0128
DME				0.135	-0.0007
Formaldehyde		0.15		1.112	0.0409
Human non-carcinogenic toxicity (kg1,4-DCB/kg product)					
Methanol	0.31	0.39	-2.92E-08	0.393	-1.4817
DME		0.15		2.043	-1.1240
Formaldehyde				18.858	-6.0607

From Figs. 12, 13, and 14, comparison between each impact indicator and the study (base case), the study's results are much higher than the other studies because other studies considered the electricity came from 100% renewable energy (hydro, wind, and solar) and Mahabir *et al.* (2021) used their electricity that could reduce their environmental impacts. In this result, the consideration focused on actual conditions that examined the impacts of valuable product production from carbon utilization that energy source was directly used in the Thailand grid mix. In comparison between each impact indicator, the study's result (100% renewable energy usage) was slightly higher than other studies due to the electricity source coming from biomass power plants, and the large amount of energy consumption of each production process. Particularly, plant efficiency, material and energy consumption, and energy sources are the main drivers for reducing emissions and developing net zero emissions and carbon neutrality [17]. The research revealed that CCUS can play a crucial role in achieving the net zero target and carbon neutrality, however, CCU commercial plant needs technology development and thorough assessments, including economic, environmental, and technological considerations.

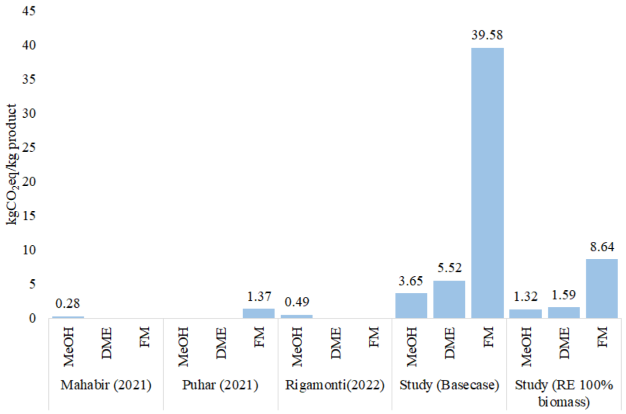

Fig. 12. Global warming potential results comparison with existing literature.

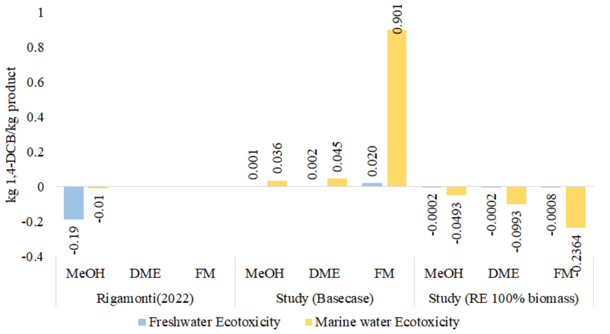

Fig. 13. Freshwater ecotoxicity and marine ecotoxicity results comparison with existing literature.

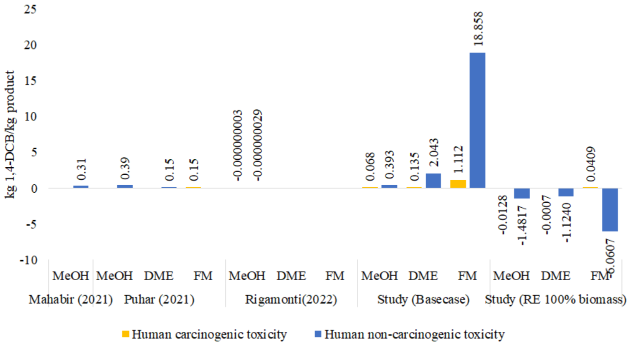

Fig. 14. Human carcinogenic and Human non-carcinogenic toxicity results comparison with existing literature.

V. CONCLUSION

The developed model achieved 99% methanol production, 99% dimethyl ether production and 60% formaldehyde production using CO_2 as the main raw material. The feedstock CO_2 gas at 1,000 kg/hr yielded 414.94 kg/hr of methanol, 269.54 kg/hr of dimethyl ether and 77.76 kg/hr of formaldehyde.

The life cycle assessment of the production processes for methanol, dimethyl ether and formaldehyde from CO_2 gas demonstrated that formaldehyde production from 1,000 kg CO_2 as feedstock produced the highest environmental impacts in all five indicators, whereas DME production from the same feedstock caused the least environmental impacts on all studied impacts categories. The results were directly related to the energy consumption since the formaldehyde consumed the largest amount of electricity according to the purification process, especially from the distillation units.

This result was confirmed by the first part of the sensitivity analysis, which indicated that all products could save net GWP up to 1,000–2,500 kgCO_2eq. based on 1,000 kg CO_2 feedstock when neglecting energy consumption. Therefore, the second part of the sensitivity analysis proposed to increase the percentage of renewable energy from biomass used as energy source in Thailand. It was found that the higher percentage of renewable energy usage, the lower net GWP obtained. These results can lead to the summary that the environmental-friendly product production with CCU implementation can help reducing the environmental impacts, especially on GWP, but it need to employ renewable energy as energy source. Further technology development and thorough assessments, particularly economic, environmental, and technological considerations together, are still necessary.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Evaluation of the environmental impacts assessment (LCA), writing, and preparation were performed by Kyaw. Model simulation was applied by Tangmesang and Phuarun. Srinophakun, Thanapimmetha, and Saisriyoot provided supplementary advice. Chiarasumran conducted the conceptualization, supervision, resources management, validation, editing and writing manuscript. All authors approved the final version.

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