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Comparative life cycle assessment of methanol production processes in China

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ABSTRACT

The surge in methanol demand as a fuel source, coupled with global resource competition, necessitates innovative routes for bulk chemical production, including methanol. China, a prominent methanol producer and consumer, drives industry expansion, raising substantial environmental concerns. This article compares the state-of-the-art "liquid sunlight" methanol production technology (CCTM) with traditional pathways (CGTM, COTM, NGTM, BOTM) through a cradle-to-gate life cycle assessment (LCA). Employing CML2001 and EI99 methodologies, we analyze ten environmental impact categories and two endpoint categories. Our study reveals the NGTM path as the cleanest for methanol production, while the CGTM route poses severe cumulative environmental impacts, 2.0 to 3.6 times worse than other methods. Environmental harm constitutes 73% to 81% of the five technology approaches' impacts, with human health impacted 10% to 12% of the time.

Keywords: Methanol Production; Environmental Impact; Clean Energy; Comparative Analysis; Sustainability

NONMENCLATURE

Abbreviations	
CGTM	Coal Gasification to MeOH
COTM	Coal Coking to MeOH
NGTM	Natural Gas to MeOH
BOTM	Biomass to MeOH
CCTM	CO2 Capture to MeOH

1. INTRODUCTION

In the 1950s, China's methanol industry emerged, undergoing accelerated technological upgrading and transformation to become a major producer. Methanol, known as "clean coal," "cheap oil," "mobile electricity," and "liquid hydrogen," finds extensive application across industries, from chemicals to energy[1]. G.A. Olah's[2] proposition of the "Methanol economy" anticipates its heightened prominence in the coming years, potentially ushering in a new fuel era. Currently, global methanol demand has doubled in the past decade, reaching 107 million tons[3]. China dominates the new production capacity in the global methanol market, boasting a 99.47 million-ton production capacity in 2022, an 8.84% increase from the previous year. In the same year, China's methanol production reached 8.306 million tons, marking a 6.27% year-on-year rise[4]. Fueled by steady domestic economic growth and accelerated advancements in automotive, electronics, and chemical industries, methanol demand continues its upward trajectory[5]. Data indicates a notable surge in methanol consumption in China, reaching 7.808 million tons in apparent consumption in 2021, a 5.96% increase from the previous year[6]. This trend intensified in 2022, with apparent methanol consumption hitting 90 million tons, reflecting a 15.26% year-on-year rise[7] Methanol, a vital chemical raw material, primarily serves downstream industries like olefins and acetic acid[8]. In 2021, methanol to olefins accounted for 50.59% of demand, followed by methanol fuel at 15.66%[9-10]. Diverse technologies presently produce methanol from fossil fuels such as natural gas, coal, crude oil, and biomass. In China, the resource distribution - "more coal, less oil, and less gas"[11-12] - has historically favored the coal-to-olefins route (58% in 2017), with coal-to-gas (17%) and natural gas-to-methanol (14%) following suit[13]. Methanol production, characterized by high energy intensity, often leads to environmental challenges. For instance, significant emissions of acidic gases (NOx, SOx, CO_2) and wastewater are commonplace[14-15] Additionally, gas leakage from various connecting valves during production is prevalent. China's growing environmental focus accentuates the significance of studying the environmental sustainability of the methanol production industry[16-17].

Most environmental assessments of methanol production focus on individual technologies or a few specific routes. However, there is a notable absence of comprehensive research on the latest carbon dioxide hydrogenation to methanol technology and other traditional energy-to-methanol methods. Notably, the

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economic and environmental aspects of the Carbon Capture and Utilization (CCU) route have garnered significant attention[18-19]. González-Garay et al.[20] conducted an exhaustive evaluation of methanol production from carbon dioxide and renewable hydrogen. process simulation and lifecycle analysis reveal that green methanol's current cost is 1.3 to 2.6 times higher than conventional fossil-based alternatives, mainly due to hydrogen pricing. Similarly, Pérez-Fortes et al.[21] assessed methanol production using hydrogen and captured carbon dioxide, indicating limited carbon emission reduction potential compared to traditional European methods. Cuéllar-Franca et al.[22] reviewed 27 life cycle assessment (LCA) studies on carbon capture and storage (CCS) and carbon capture and utilization (CCU) technologies, highlighting CCU's heavy reliance on renewable energy and its associated environmental imbalances. They conclude that LCA research should encompass carbon dioxide purification steps, renewable electricity electrolysis for hydrogen production, and complete lifecycle analysis for meaningful insights. Thonemann[23] conducted an analysis of LCA-based CO_2 chemical production, finding no CO_2-based technology superior in all impact categories to conventional methods. Methanol production pathways, including biomass gasification and CO_2 recovery from fossil fuel-fired power station flue gases, have been explored by Shamsul et al.[24], addressing bio-methanol's potential as a renewable resource, considering global demand, economic assessment, power density, and potential applications[25]. Zhen et al.[26] describe various methanol production approaches, encompassing coal, natural gas, coke-oven gas, hydrogen, and biomass. Dalena et al.[27] review prevalent feedstocks (natural gas, CO2, coke/biomass) and methanol production processes, including membrane reactor technology's catalytic conversion of methanol to high-grade hydrogen. Additionally, Blumberg et. Al[28] address methanol synthesis economics with different reforming technologies, evaluating process efficiency for steam reforming, autothermal reforming, and dry methane reforming, along with economic and sensitivity analyses. Gautam et al. present a comprehensive overview of thermo-chemical and biochemical routes for sustainable bio-methanol production from waste biomass. Chen Z et al.[29] conducted a "cradle to gate" life-cycle assessment of COTM, CGTM, and NGTM, offering a comparison of three traditional technology roadmaps. However, research comparing the LCA of all methanol production routes in China remains a gap in the current body of work.

The preceding study delves into the economic and environmental consequences of diverse methanol pathways. However, a comprehensive examination of the sustainability's life cycle impact across these routes has yet to be thoroughly investigated. To truly comprehend the potential ramifications of implementing such routes, there is a crucial need to quantify the environmental, human, and ecological effects of CCU chemicals, particularly green methanol. This will aid in devising efficient strategies to alleviate these potential damages.

2. MATERIALS AND METHODS

Per ISO guidelines (ISO, 2006a, b)[30], the LCA study involves four main steps: (1) defining goals and scope, (2) conducting a life cycle inventory (LCI) analysis, (3) performing a life cycle impact assessment (LCIA), and (4) interpretation. The study's foundational element lies in clarifying objectives and scope, depicted in Figure 1, from which the other three stages evolve. Initial stages encompass establishing the study's subject, gathering and scrutinizing data to pinpoint raw material sources, consumption patterns, and emissions. Subsequently, assessment indicators are established, and finally, results are interpreted. Notably, the eFootprint software is a highly favored tool within this field.

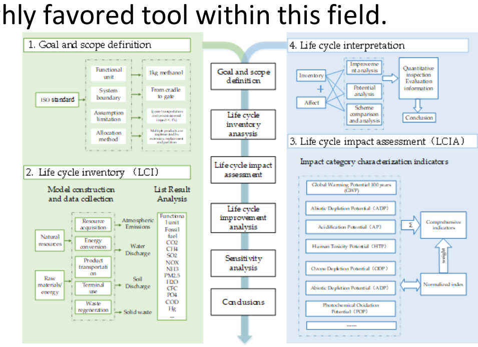

Figure 1 Life Cycle Assessment Flowchart based ISO 2006a, b

2.1 Goal and scope definition

This study compares the environmental impacts of five common methanol production routes: CGTM, COTM, NGTM, BOTM, and CCTM. These methods encompass both conventional and novel approaches, involving methanol production from coal, natural gas, biomass, and the direct capture of carbon dioxide, coupled with hydrogenation using renewable energy sources. The specific production pathways are illustrated in Figure 2. The study adopts a "cradle to gate" boundary, focusing on raw material extraction to methanol production, excluding infrastructure and facility-related impacts. Wastewater is treated, recycled, and solid waste is sent to a nearby landfill. Exhaust gases are either reused or flared in the fuel gas system. As the catalyst used in the process has a 3-5 year replacement cycle and remains unchanged during methanol production, waste catalyst is not considered in solid waste. Notably, methanol application is not addressed due to the uniform post-production steps across routes.

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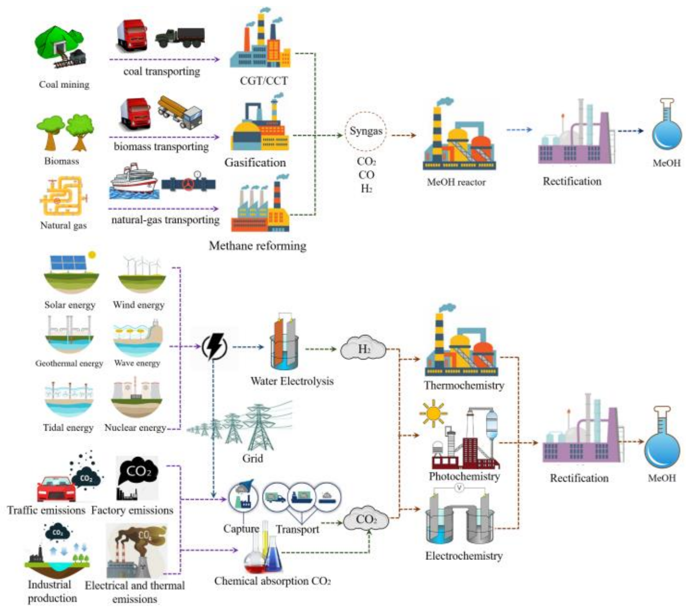

Figure 2 Overview of different methanol WTP pathways

2.2 Life cycle impact assessment methods

Material-energy data for each technology route's life cycle were sourced from published data from plants, real-world projects, or academic literature. To enhance realism and credibility, challenging-to-obtain data were replaced with simulated data where necessary. In order to ensure the study's robustness, eFootprint's database was used to select specific secondary energy sources that align with China's resource environment for indirect energy and material data.

The main inputs for the CGTM and COTM routes encompass coal, oil, water, power, and process outputs. Equations (1-3) outline the key reactions within the methanol synthesis reactor, with a molar ratio of approximately 2 between H_2 and CO_2 during the reaction.

$$CO+2H_2 \rightarrow CH_3OH, \quad \Delta H= -90.64 kJ/mol \tag{1}$$

$$CO_2+3H_2 \rightarrow CH_3OH+H_2O, \quad \Delta H= -49.47 kJ/mol \tag{2}$$

$$CO+H_2O \rightarrow CO_2+H_2, \quad \Delta H= -41.47 kJ/mol \tag{3}$$

The study employs eFootprint software for specialized production models. The CML2001 and Eco-indicator 99[31] methodologies characterize, normalize, standardize, and weight the life cycle environmental load inventory data for each route, enabling the calculation of the corresponding environmental impact values. Please refer to Figure 3 for the methodological framework.

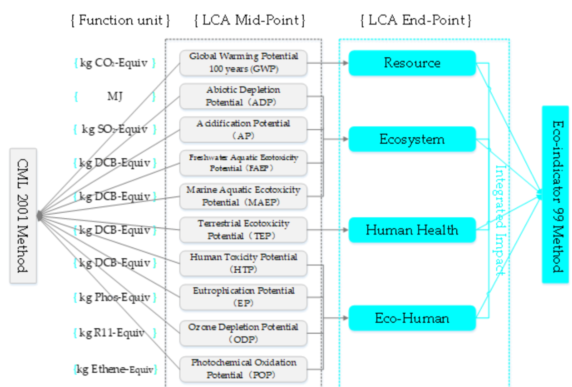

Figure 3 The map of methodology

The five methanol processes are commonly evaluated and compared at the mid-point (MP) and end-point (EP) levels. The MP level evaluation is problem-oriented and focuses on environmental issues, evaluating the environmental mechanisms that link pollutant emissions to harm, while ignores the effects of environmental degradation on resources, ecosystems, and humans. The EP level assessment is a damage-oriented technique that assesses the detrimental effects on ecosystems and human health. The CML2001 technique was used to assess environmental impacts at the MP level, and ten typical impact categories were chosen as MP level indicators. At the EP level, impacts on ecosystems and human health were evaluated using eight ecological indicators, as given in Table 6, utilizing the Eco-indicator The main gases causing global warming are CO_2, CH_4, and NO_2, with CO_2 being the reference gas.

Table 1 Impact categories for the Eco-indicator 99 models

Damage	Category
Ecosystem Quality (EQ)	Land conversion LC Acidification/Eutrophication AC/EC Ecotoxicity EC
Human Health (HH)	Climate Change CC Radiation RA Cancer ecotoxicity CE Inorganic IR Organic OR

Human health damage is gauged using disability adjusted life years (DALY), encompassing years of life lost and impaired. Ecosystem quality harm is expressed as the potentially disappeared fraction (PDF), representing the percentage of species that might vanish due to environmental influences, signifying ecosystem degradation. Inventory analysis computes environmental pressure for each process unit, followed by comprehensive analysis to evaluate potential environmental impacts.

3. RESULTS AND DISCUSSION

The five common methanol pathways share similar ingredient profiles, utilizing 13 distinct input materials from the environment, encompassing both non-renewable and renewable resources. Emissions are categorized into inventory, air, water, and soil emissions. These emissions comprise heavy metals, inorganic and organic chemicals, with topsoil, waste, and degraded goods as the primary stockpiles. Notably, heavy metals and inorganic compounds dominate pollutants released into the air, water, and agricultural and industrial soils.

As a leading producer and consumer, China's methanol industry is expected to grow alongside emerging downstream industries. However, environmental concerns arise due to its heavy reliance on fossil fuels for production. This study employs the eFootprint software to comprehensively assess the environmental impact of various methanol production pathways – coal to methanol (CGTM), coke oven gas to methanol (COTM), natural gas to methanol (NGTM), biomass to methanol (BOTM), and carbon dioxide hydrogenation to methanol (CCTM). Through a life cycle evaluation, this research examines the environmental footprint of these pathways.

3.1 LCA results and Environmental performance on MP level analysis

3.1.1 Comparative total impact analysis

Figure 4 illustrates the impact categories among the five methanol production routes. The highest MAETP value results from emissions like ammonia nitrogen, oil substances, phosphate, sulfides, and heavy metals during methanol production. AP, EP, POCP, FATEP, and TETP values have similar magnitudes, around 10 orders of magnitude, indicating comparable acidic and organic gas emissions and their impacts on freshwater resources and terrestrial ecotoxicity. In contrast, ODP holds the lowest value, indicating minimal ozone layer depletion.

In the CGTM route, all midpoint influence values peak, except for HTP and POCP, signifying its heightened environmental load. Notably, POCP and HTP are lower than those in the CCTM route, registering at 669 kg DCB-Equiv and 0.909 kg Ethene-Equiv, respectively. The ecotoxicity (FAETP/MAETP/TETP) and acidification (AP) and eutrophication (EP) effects within CGTM and COTM predominantly result from electricity and steam production processes. Apart from ODP, the COTM route's environmental impact values rank second to CGTM's, with CGTM's nine impact categories being 1.91-2.58 times greater. This highlights the greater environmental advantage of coal coking to methanol over coal gasification. Moreover, the coal coking process releases substantial carbon oxides and nitrogen oxides, thus enhancing acidification AP and eutrophication EP damage values in COTM.

Among the five methanol routes, the NGTM route displays the lowest impact in EP/HTP/ODP/POCP/MATEP categories, signifying comparatively lower industrial waste discharge. Additionally, it contributes the most to the ADP category and registers significant values in GWP, AP, EP, POCP, FATEP, MATEP, and TETP. These outcomes can be largely attributed to environmental effects stemming from natural gas leakage during mining and processing stages. Despite its notable MATEP influence, it remains the smallest among the five routes, at 1.05E+05 kg DCB-Equiv—half of coal gasification to methanol and one-third of coke oven gas to methanol, similar to BOTM and CCTM. Noteworthy is the minimal impact of EP/HTP/POCP/MATEP categories across all routes, underscoring reduced nitrogen, phosphorus, and volatile organic compound emissions during the natural gas to methanol stages.

The BOTM process boasts a negative total GWP value, indicating reduced greenhouse gas emissions compared to consumption. AP/EP/POCP/FAETP/MAETP/TETP values align closely with NGTM, implying similar acidic and organic gas emissions and ecotoxicological impacts. BOTM's POCP is the lowest among all routes at 3.32E-10kg R11-Equiv, demonstrating minimal acidification or eutrophication impact on land environments. Notably, its AP value is 3.206 kg SO2-Equiv, while EP is 0.3308 kg Phos-Equiv. BOTM records the lowest ADP among the five paths, utilizing the fewest resources overall, primarily due to fossil energy consumption. Biotoxicity HTP primarily stems from pesticides in rice straw growth and CO, SO2, and NOX emissions during methanol production. The terrestrial ecotoxicity TETP value, akin to AP and FATEP, ranks lowest among the five routes.

The CCTM route demonstrates the highest biotoxicity HTP and POCP among all routes, yet experiences the least variance in ecotoxicity across environments (FAETP/MATEP/TETP). Consequently, CCTM is relatively less clean, with higher EP/ADP/ODP/POCP/FATEP/TETP values than coke oven gas-derived methanol, indicating elevated environmental pollution levels.

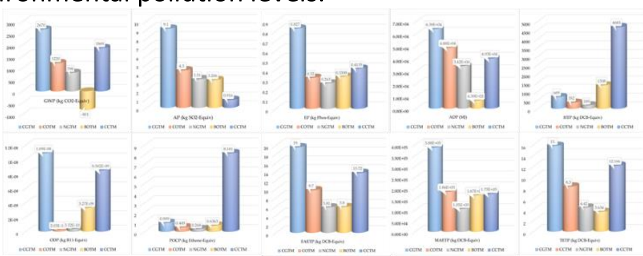

Figure 4 Total impact analysis to the LCIA of typical technical routes

3.1.2 Comparative process impact analysis

Figure 5 displays the fractional share of each technology unit in the overall technology process and the share of each technology unit in the 10 categories of impacts for each of the five technological pathways for methanol.

The CGTM technology route's coal treatment stage (65.2%), syngas production stage (19.85%), and methanol synthesis stage (15.85%) have the greatest fossil energy consumption ADP. More than 50% of the syngas production stage's contribution to the AP, FATEP, MATEP, and TETP impacts comes from the release of radioactive elements like Kr during the production of electricity and steam. For GWP, EP, and HTP, this contribution is over 40%, and for ODP, it is over 90%. Additionally, the manufacturing of methanol makes up around 40% of these effect categories. The fact that the carbon fixed in fossil fuels is released into the atmosphere as CO_2 to create the greenhouse effect is another reason why the AP contribution is positively correlated with the GWP. In order to lessen the greenhouse effect of methanol manufacturing, CO_2 must be recovered from exhaust gases.

The entire stage of the COTM technology pathway is an energy-intensive process, however the effects of the methanol synthesis stage account for a disproportionate amount (>75%) of the total energy use. Similar to the CGTM route, 80.1% of the effects of ADP come from the stage of coal mining and treatment. Second, the impacts of GWP and POCP in the coal handling stage are rather significant, accounting for 20.3% and 18.95%, respectively. This is mostly because the coal handling stage releases a lot of CO_2 and NOX. Additionally, EP and ODP have the biggest effects during the coke production stage. This is largely because this step uses a lot of steam and electricity while producing N, P, and other radioactive elements.

The natural gas extraction and processing stages in the NGTM technology route have significant environmental effects (25%). In addition to its largest contribution in the ADP category, the GWP, AP, EP, and POCP categories also have relatively large shares, which are primarily due to environmental impacts caused by natural gas leakage during the extraction and processing stages, such as acidic gases, methane, and hydrocarbon gases. With MAETP and TETP accounting for nearly 100% of the total electricity consumed during the gas mixture's reforming and methanol production stages, which had high environmental impacts (70%–99%), it can be concluded that the methanol production stage has the greatest influence on both marine and terrestrial ecosystems.

The BOTM technology route results in negative GHG emissions as atmospheric CO_2 is transformed to methanol, which perfectly captures the benefits of biomass in the carbon cycle. However, the gasification process stage has the highest emissions of NO_X, SO_2, and total suspended particulate matter (TSP) in this stage, according to the ODP, which is more specific among all impact categories and reaches up to 55.21%. This is primarily because so much renewable energy is used in this stage. The GWP AP EP ADP POCP FAETP percentage for the methanol manufacturing stage ranges from 65% to 85%, indicating that it significantly pollutes freshwater resources and the atmosphere. Overall, though, the BOTM method is far superior at reducing the effects of global warming.

The CO_2 capture stage of the CCTM technological route causes the most environmental damage, accounting for roughly 70% of all environmental effects, which can be linked to the usage of power and steam in the eFootprint process. Of all the effect categories, ODP is the most focused and accounts for 80.15% of the overall impact, with the majority of its contribution coming from the hydrogen production stage. This is because the manufacturing of hydrogen requires a significant quantity of renewable energy, such as the creation of polysilicon panels for renewable energy construction and the production of resins for the building of windmills, both of which emit ozone-depleting compounds.

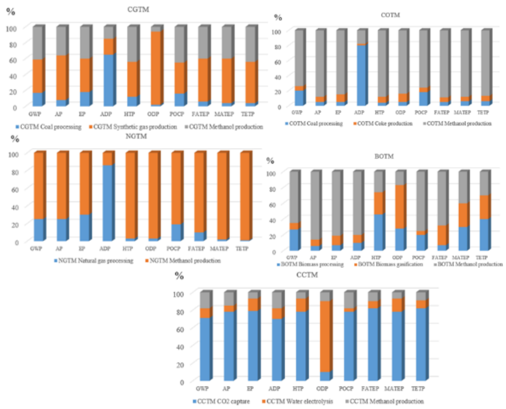

Figure 5 Contribution of typical process of the five methanol routes on MP level

3.2 LCA results and Environmental performance on EP level analysis

3.2.1 Comparative total impact analysis

Both CGTM and COTM manufacture methanol from coal, which results in the discharge of a considerable number of hazardous gases and compounds such as CO2, SO2, and NOX, which destroy the ecology. In comparison to CGTM and COTM, NGTM has a reduced environmental impact. Natural gas resources are typically found in more remote places, therefore mining has a lower environmental impact. Furthermore, because natural gas is cleaner than coal, the process of producing methanol has a low impact on acidification and eutrophication of the land. NGTM use renewable biomass as a fuel in a sequence of chemical reactions to produce methanol. NGTM has a lower impact on land resources than the usage of fossil fuels. Crop residues, wood wastes, and industrial organic wastes, among other things, are recycled during the biomass production process. This decreases trash pollution on the ground and enhances land resource usage. Furthermore, the carbon dioxide created by BOTM can be absorbed by plants, forming a biological cycle that does not significantly acidify or eutrophicate the land environment. The environmental impact of CCTM is mostly determined by the energy source and carbon dioxide emissions employed in the manufacturing process. Using clean energy as the energy input and being able to absorb and store carbon dioxide efficiently, the environmental impact of renewable energy equipment is primarily focused on in the manufacturing process of photovoltaic panels.

According to the research in Figure 6, all routes have a stronger impact on ecosystems in terms of endpoint impact category, implying that these methanol-manufacturing methods will damage water and land. Damage to ecosystem quality and human health caused by CGTM is 334 PDF/m2 a and 0.0159 DALYs, which are 2.1, 3.6, 3.5, and 1.6 times higher than those caused by COTM, NGTM, BOTM, and CCTM, respectively. We can see that CGTM causes the most ecological harm to water resources, land resources, and so on, while CCTM causes damage similar to CGTM, and the value of CCTM's influence on the ecosystem is higher than that of COTM, NGTM, and BOTM. Among the human health consequences, the overall value of harm to human health (Human Health) of CGTM is 2.15 times that of COTM, whereas the damage values of NGTM and BOTM are lower, 0.00144 DALY and 0.00454 DALY, respectively. Overall, the impact of each technology path on human health is significantly smaller than the impact on ecosystems, indicating that each route's potential to alter ozone layer depletion, eutrophication, and global warming is not as great as the impact on ecosystems.

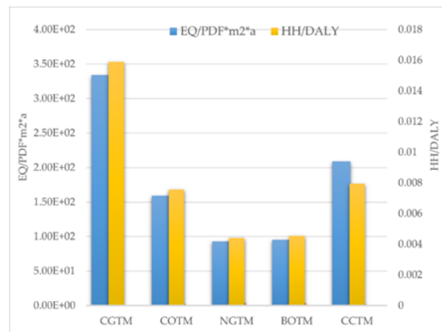

Figure 6 Environment performances for the five methanol technology on EP level

As shown in Figure 7, the main impact categories for CGTM COTM NGTM in terms of ecosystem quality were acidification/eutrophication (AC/NC) and ecotoxicity (EC) (70.06%, 54.66%, and 51.3%, respectively). The consequences of LU, EC, and AC/EC were roughly distributed among the three major pathways of CGTM, COTM, and NGTM, with a substantial proportion of acidification and eutrophication, and the impacts on ecosystem quality in terms of land resource use all accounting for 2%. BOTM requires a significant number of crops, therefore its land resource usage accounted for 57%, the greatest compared to the other routes, and the land use value of all other technological routes is between 2% and 5%, which is the resource that the biomass must use throughout the growth stage. In CCTM, the proportions of each influence component are identical to those in COTM, and the proportions of EC and AC/EC are about 1:1.

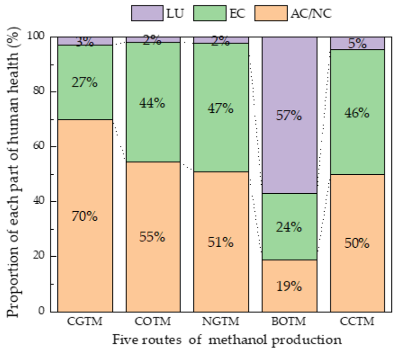

Figure 7 Relative damage to ecosystem quality (EQ) for the five methanol routes on EP level

It is derived from Figure 8 that carcinogenic effects, climate change and respirable inorganics are the three main influences on these five technology routes as far as human health is concerned. CGTM has a negligible effect on radiation and respirable organics, but has the greatest effect on respirable inorganics, accounting for 44.40% of the overall influence. CCTM has the greatest influence on carcinogenic effects (48.95% of overall influence), followed by respirable inorganics, and a relatively minor impact on climate change. The percentage of IR in the five routes with human health implications decreased by 44%, 37%, 27%, 10%, and 1%, respectively, indicating that the fraction of respirable inorganics has been decreasing. With a high percentage of 37%, RA has the highest value in BOTM, whereas the other routes have less radiation impact. The impact of the five paths on climate change ranges from 14% to 35%, with the last being the most impactful. According to Fig. 15, the influence of CCTM on human health is second, and the share of CE is as high as 50% of its influencing variables, and the percentage of OR is also the largest compared to the other routes, at 19%.Ionizing radiation (RA) and respiratory organics (OR) have insignificant impacts in CGTM and COTM, whereas respiratory inorganic (IR) has an influence ranging from 37% to 44%, which is related to the current study's system boundary specification. The data source company recycles the exhaust gas from the coal gasification (coal coking) process for the fuel gas system. The exhaust gas treatment process of coal to methanol production was taken into consideration in this study. The amount of organic stuff released into the atmosphere is thereby greatly decreased.

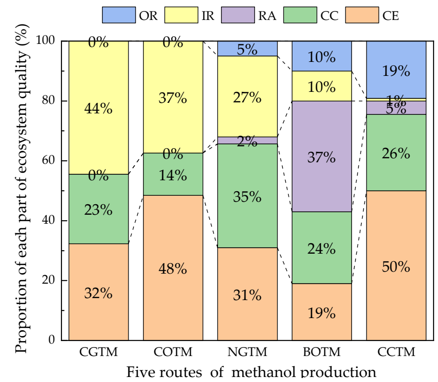

Figure 8 Relative damage to human health (HH) for the five methanol routes on EP level

3.2.2 Comparative process impact analysis

As observed in Figure 9, the coal gasification process's acidification and eutrophication damage values are increased due to the syngas generation process of the CGTM process's high emissions of carbon and nitrogen oxides. Both the ecosystem and human health have suffered severe harm. Particularly, the COTM's methanol synthesis phase causes more harm to the environment and to people's health. Compared to previous steps in the COGM, NGTM, and BOTM pathways, the methanol synthesis stage is more harmful to the environment. In CCTM, the CO2 capture process is the major factor contributing negatively to the ecosystem and human health. This is mostly because of the high value of ecosystem impacts brought on by the average power consumption in the CO2 capture process, which makes its percentage occupy 79%. The steps of hydrogen production and methanol synthesis, however, have relatively minor effects on ecosystems and human health when compared to other approaches. This highlights the new methanol route's positive environmental effects on water eutrophication, energy efficiency, greenhouse gas emissions, and ozone layer depletion.

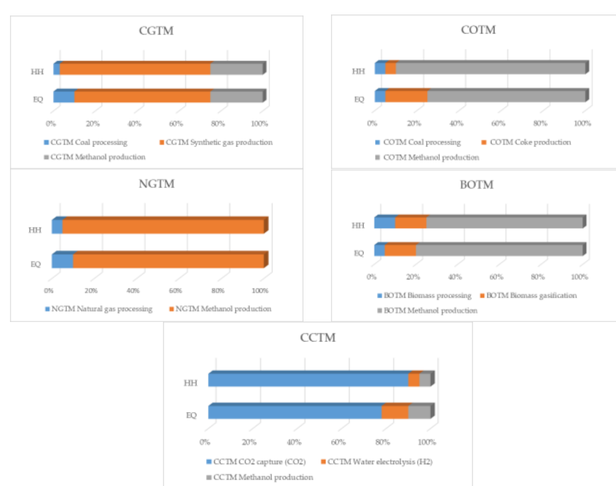

Figure 9 Comparative results of ecosystem quality relative damage of five methanol technologies

An investigation of the effects on human health and key ecological characteristics at various phases of production is shown in Figure 10. Climate change, ionizing radiation, carcinogenicity, and respirable organic/inorganic ratio are all used to examine the effects on human health. Three factors—land conversion, acidification and eutrophication, and ecotoxicity—are used to examine the effects on habitats.

Ecotoxicity is the first. The CGTM and COTM procedures create poisonous and dangerous byproducts including benzene, phenol, cyanide, etc. that are harmful to human health and cause malignancies, respiratory illnesses, and other conditions. The amount of coal needed by CGTM and COTM to produce 1 ton of methanol is 1.8 tons and 1.5 tons, respectively. Statistics show that CGTM uses energy at a rate of about 50% while COTM uses energy at a rate of just about 20%. According to studies, the COTM's SO_2 and NOx emissions are 4.35 and 11.43 million tons, compared to the CGTM's 24.44 and 43.41 million tons, indicating a stronger impact on air quality. The occupation of substantial land resources is necessary for the mining and use of coal, although the effects of CGTM and COTM on land use are negligible. The effects of NGTM on ecosystems and land use are minimal. The percentage of AC/EC ranges from 20.35% to 60.75% for almost all technology routes, with the gasification stage of CGTM and the CO_2 capture stage of CCTM having the highest percentages. This shows that any of the stages have a significant impact on the acidification and eutrophication of air and land. Compared to AC/NC and EC, the LU % has a minimal impact. The environmental friendliness of the two technology pathways can be seen in the fact that the AC/NC+EC values of the biomass gasification stage of the BOTM are the lowest and the AC/NC+EC values of the coal preparation stage of the COTM are the greatest.

Human health is the next area of concern. In CGTM, the syngas generating stage has the largest proportion of CE (40.15%), while the coal preparation step has the highest amount of radiogenic RA (30.6%). However, with a proportion of just 9.8%, the methanol manufacturing step has the lowest radiogenicity. The coal gasification process in COTM has an OR percentage as high as 59.86%, which indicates that these two processes have significant effects on human carcinogenicity and, separately, the respiratory tract. In COTM, the CC RA IR of the methanol production stage is all 5%–10% higher than that of the coke oven gas production stage, and the effect of coal preparation stage on CE CC RA IR is similar, with the percentage of them all being around 10%. In addition, the RA of the methanol production stage is the highest, reaching as high as 25.3%.

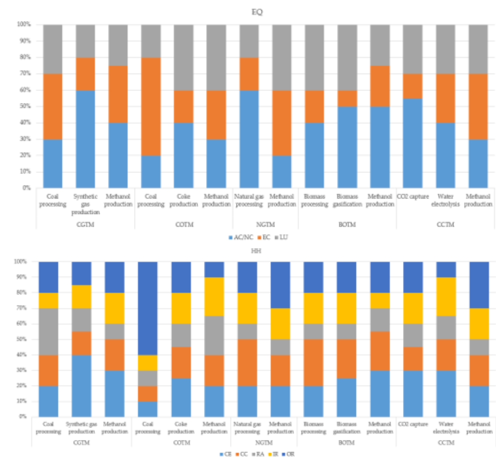

Figure 10 Comparative results of human health damage caused by five methanol technologies

4. CONCLUSIONS

The typical technology routes for methanol production in China are CGTM, COTM, NGTM, BOTM and CCTM. This paper uses the LCA method to analyze each route's combined environmental impacts, process impacts on the environment. It also examines each route's 10 types of environmental impacts and 2 types of endpoint impacts at the midpoint level. The results show that,

1. The CGTM technology route exhibits the most significant combined environmental impact, surpassing that of the other four routes by 2.0 to 3.6 times, while NGTM stands out as the cleanest method for methanol production.

2. Among these routes, CGTM registers the highest environmental impact, primarily attributed to the syngas production stage. COGM and NGTM, on the other hand, predominantly contribute to environmental effects during the methanol production stage. Notably, the CO_2 capture process within CCTM accounts for the most substantial environmental impact.

3. Across these five technological approaches, environmental degradation constitutes 73% to 81% of the impacts, with human health being impacted 10% to 12% of the time. Sensitivity analysis highlights electricity as the most responsive indicator to environmental implications. This holds true for power consumption during syngas production in the CGTM route and electricity usage in methanol synthesis stages within the COTM, NGTM, and BOTM routes. The sensitivity of steam consumption in the CCTM route is also notable.

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