Study of bioethanol life cycle greenhouse gas emissions based on a hybrid life cycle approach

Xiaoze Wang

Department of economics, Nanjing University of Aeronautics and Astronautics, Nanjing, 211100, China

wxzxmy2021@163.com

Abstract. A hybrid life cycle assessment model was constructed based on China's 2018 EIO-LCA model and PLCA method, and life cycle GHG emissions including corn ethanol, cassava ethanol and sweet sorghum ethanol were calculated and disaggregated to the remaining 42 industry sectors. The study showed that the life cycle GHG emissions of corn ethanol were 4877.78 kgCO_2eq/t ethanol, which was the highest among the three types of ethanol, and the life cycle GHG emissions of cassava ethanol were 4183.80 kgCO_2eq/t ethanol, which was the lowest among the three types of ethanol. Of the indirect emissions from the three types of ethanol, the sectors that emit the most are all in the production and supply of electricity and heat, which account for 30-32% of the indirect emissions. In addition, of the three types of ethanol, only cassava ethanol has lower GHG emissions than conventional gasoline, with a reduction of 6.1% relative to conventional gasoline. The hybrid life cycle approach can calculate the GHG emissions of bioethanol in a more comprehensive way and can reflect the distribution of indirect emissions across sectors, which is instructive for relevant emission reduction policies.

Keywords: EIO-LCA, Bioethnol, Greenhouse gas emissions.

1 Introduction

With the rapid economic development, China's total energy use and carbon dioxide (CO_2) emissions are also rising, and China has become the world's largest energy and CO_2 emitter [1]. In the context of the global development of low-carbon economy, the development of renewable energy is imminent. In recent years, major energy consuming countries have competed to seek new energy to replace oil. Bioethanol, as a renewable energy and can be used as an alternative fuel for vehicles, has attracted wide attention from all countries. However, there is still controversy in the academic community on whether bioethanol can reduce greenhouse gas emissions in the life cycle [2]. Therefore, the research on the life cycle greenhouse gas emissions of bioethanol has certain guiding significance for China to make emission reduction decisions of the transportation sector.

Z. Zhan et al. (eds.), *Proceedings of the 2024 10th International Conference on Humanities and Social Science Research (ICHSSR 2024)*, Advances in Social Science, Education and Humanities Research 858,
https://doi.org/10.2991/978-2-38476-277-4_69

There are three kinds of accounting methods for greenhouse gases in the life cycle of bioethanol: process life cycle assessment (PLCA), input-output assessment and hybrid life cycle assessment. At present, the research on greenhouse gas(GHG) emissions of bioethanol is basically based on the PLCA. Chendong used the basic theory of life cycle to evaluate the GHG emission of second-generation cellulosic ethanol [3], Geng Zhongfeng and others used PLCA method to evaluate the GHG emission of cassava ethanol [4]. However, the PLCA method has the problem of boundary definition, and the evaluation criteria are not consistent between different studies. Therefore, the conclusions obtained are highly independent, lacking the importance of horizontal comparison, and the PLCA method does not fully consider indirect emissions, resulting in truncation errors [5-6]. In addition, in order to obtain a detailed life cycle list, a large amount of resources are invested [7]. In view of the above limitations of the PLCA method, some scholars began to use the method of combining the economic input-output life cycle assessment method with the PLCA method to study the greenhouse gas emissions of bioenergy [8-10]. Domestic scholars have also used this method to study the life cycle greenhouse gas emissions of cassava ethanol in China [11]. In addition, the distribution of indirect emissions in the production chain also has an important impact on the life cycle emissions of bioethanol, but there are few studies on this in the existing literature [12].

Based on the EIO-LCA model, this paper establishes a hybrid evaluation model for accounting the GHG emission of bioethanol life cycle, and reflects the greenhouse gas emissions of bioethanol life cycle in China by using the input-output table of China in 2018 and the relevant emission data of corn, cassava and sweet sorghum. The hybrid life cycle assessment model is suitable for the life cycle greenhouse gas accounting of bioethanol produced from various raw materials. This paper uses the model to account for the life-cycle GHG emission of corn, cassava and sweet sorghum ethanol as an example. Three aspects are analysed: direct and indirect emissions at each stage of the life cycle, the distribution of indirect emissions across the sectors of the production chain, and a comparison with the life cycle emissions of conventional gasoline.

2 Methods

2.1 Life Cycle Framework

Life Cycle Assessment (LCA) is a method for measuring the environmental impact of a product at all stages, including production, transport, use and recycling, and is a commonly used method for measuring the carbon footprint of a product [13]. LCA consists of four parts, namely, definition of objectives and scope, analysis of inventories, impact assessment, and interpretation of results. In this paper, the system boundary of the three types of ethanol includes the stages of feedstock cultivation, feedstock transport, bioethanol production, bioethanol transport, and bioethanol use, which are shown in Fig. 1 [14], and the cultivation and production processes of the three types of ethanol are shown in Fig. 2. The system boundary of conventional gasoline includes the processes of crude oil extraction, transport, gasoline production, and combustion [14].

The life-cycle GHG emissions of the three types of ethanol accounted for in this paper include both direct and indirect emissions. Direct emissions refer to the emissions generated during the production and use of a product, which in this paper mainly include the emissions generated by ethanol combustion and nitrogen fertiliser application leading to the nitrogen fertiliser effect, and indirect emissions refer to the emissions caused by the various sectors of the production chain during the production process of the three types of ethanol, the production of the three types of ethanol requires the input of a certain product i, and the production of i gives rise to emissions and also requires the input of product j, in that order (i and j both belong to the 42 sectors), the indirect emissions are the sum of the emissions from the upstream stages of all these production processes.

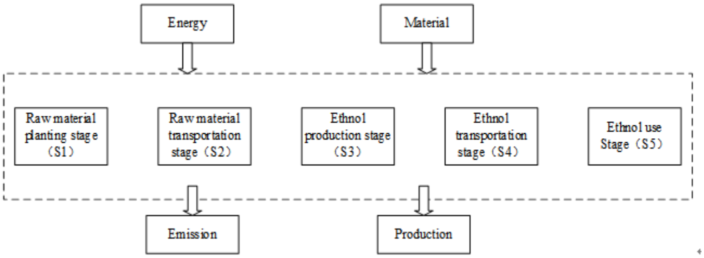

Fig. 1. Bioethanol life cycle system boundary

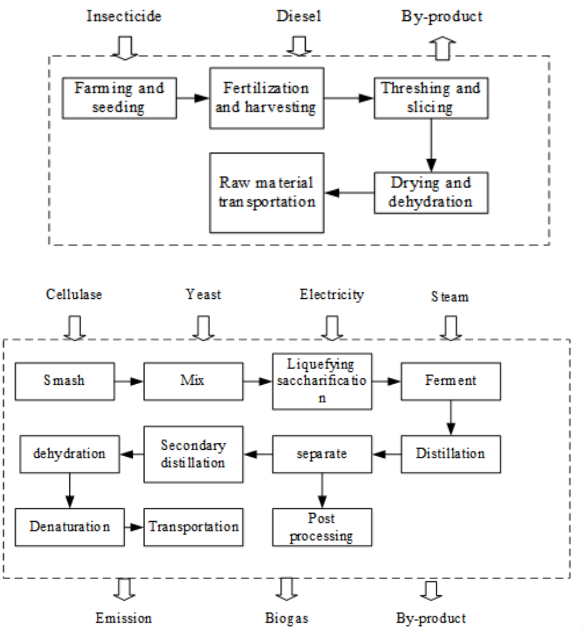

Fig. 2. Planting and production process

2.2 Construction of an EIO-LCA Model Incorporating Bioethanol Segments

Hendrickson et al [15-16] proposed the EIO-LCA methodology, which aims to investigate the potential environmental impacts of a product during its production process. EIO-LCA is based on two core assumptions: homogeneity and proportionality. The former means that there is a positive relationship between the environmental impacts of a product and the producer price within the same sector, while the latter means that there is also a positive relationship between the inputs and outputs of a product sector within the same sector. EIO-LCA is widely used to complement PLCA in terms of truncation error.

EIO-LCA consists of an economic input-output table and an environmental impact factor (EIF), i.e., columns representing "environmental" sectors are added to the input-output table, and the value of each row represents the pollutant "output" of an industry. The EIO-LCA pollutant emission factors differ from traditional environmental input-output methods in that they take the form of a diagonal matrix, which helps to disaggregate the environmental problems caused by final demand into the various parts of the production chain.

Let Ri be the direct GHG emission factor for sector i. Ri is given by:

$$R_i = c_i / x_i \tag{1}$$

The direct GHG emission factor R_i is the CO_2 equivalent emitted per unit of output in sector f. The matrix R of direct GHG emission factors is formed from R_i.where c_i is the direct GHG emissions of sector i and x_i is the total output of sector i. By substituting the carbon emission coefficients from the China Statistical Yearbook and the data in the combined and split 43 sectoral input-output tables into equation (1), R_i can be derived through matrix operations.

The EIO-LCA model is [16]:

$$B = R(I - A)^{-1} y \tag{2}$$

B is the vector of GHG emissions from each sector due to final demand y. R is a diagonal matrix whose diagonal element R_i is the amount of GHG directly emitted per unit of monetary output in sector i. The GHG emissions from each sector can be calculated based on the combined and split input-output table and the above diagonal matrix R.

A significant advantage of EIO-LCA is that it adopts a top-down approach to modelling that considers the entire national economy as the boundaries of the system, covering the entire process of a product from upstream to downstream, thus avoiding truncation errors. In addition, it uses mathematical models to describe the interactions between different sectors of the economy, enabling a rapid assessment of the environmental impact of a product or service. In spite of the aforementioned advantages of EIO-LCA, it does not realistically represent the production process of a product and therefore cannot completely replace PLCA [17].

2.3 Hybrid life-cycle Assessment

The hybrid LCA method integrates the PLCA and EIO-LCA methods within a single analytical framework, which retains the advantages of PLCA with its direct product-specific approach and avoids the truncation error in the calculation of indirect GHG emissions [18]. It also makes use of existing input-output tables, avoiding the problem of difficult data collection in the PLCA method and reducing the resource input in accounting.

In this paper, the direct emissions of each stage are calculated by PLCA method, and the indirect emissions are calculated by EIO-LCA method, and the whole life cycle GHG emissions are the sum of direct and indirect emissions of each stage. The following formula shows the life cycle GHG emissions of bioethanol calculated by hybrid life cycle.

$$GHG_H = GHG_E + GHG_P \quad (3)$$

GHG_H is the total GHG emissions from the life cycle of bioethanol, GHG_E is the emissions calculated by EIO-LCA method, and GHG_P is the emissions calculated by PLCA method[18].

3 Results

3.1 Analysis of GHG Emissions in the Life Cycle of Various Types of Ethanol

Since most studies on bioethanol GHG emissions do not include photosynthesis in the life cycle, the GHG emissions from photosynthesis have not been included in the total life cycle emissions of the various types of bioethanol in this subsection in order to facilitate comparisons with related studies. The results for the three types of ethanol by phase are shown in Tables 1- 3.

Table 1. GHG emissions at each stage of corn ethanol life cycle. unit(kgCO_2eq/t ethanol)

Emission type	Material planting	Fuel production	Transportation	combustion	Life cycle
Direction emission	196.42	1420.12	405.2	1913	3934.74
Indirection emission	481.57	387.95	73.52	0	943.04
Total	677.99	1808.07	478.72	1913	4877.78
Percentage	13.9	37.1	9.8	39.2	100

Table 2. GHG emissions at each stage of cassava ethanol life cycle unit(kgCO_2eq/t ethanol)

Emission type	Material planting	Fuel production	Transportation	combustion	Life cycle
Direction emission	124.70	1175.42	212.22	1913	3425.34
Indirection emission	390.49	315.40	52.57	0	758.46
Total	515.19	1490.82	264.79	1913	4183.80
Percentage	12.3	35.7	6.3	45.7	100

Table 3. GHG emissions at each stage of sweet sorghum ethanol life cycle

Emission type	Material planting	Fuel production	Transportation	combustion	Life cycle
Direction emission	141.53	1341.15	242.13	1913	3637.81
Indirection emission	465.51	372.52	65.19	0	903.22
Total	607.04	1713.67	307.32	1913	4541.03
Percentage	13.4	37.7	6.8	42.1	100

Among the three types of ethanol, corn ethanol had the highest total life cycle GHG emissions of 4877.78 kg CO_2eq/t ethanol, sweet sorghum ethanol had the second highest total emissions of 4541.03 kg CO_2eq/t ethanol, and cassava ethanol had the lowest total life cycle GHG emissions of 4183.8 kg CO_2eq/t ethanol. Emissions from the production and combustion stages of ethanol in the three types of ethanol accounted for 76.3%-81.4% of the total emissions, with cassava ethanol accounting for the highest share and maize ethanol accounting for the lowest. Feedstock cultivation accounted for 12.3-13.9% of total emissions among the three types of ethanol, with corn ethanol accounting for the highest share and cassava ethanol for the lowest. The transport phase accounted for 6.3-9.8% of total emissions among the three types of ethanol, with corn ethanol accounting for the highest share and cassava ethanol the lowest. From the point of view of direct and indirect emissions, direct emissions accounted for 80.1-81.9% of the total emissions, which is not a big difference, and indirect emissions accounted for 19.1-19.9% of the total emissions. Ethanol production and combustion are the most important sources of direct emissions, accounting for 84.7-90.2% of the total direct emissions, with cassava ethanol accounting for the highest percentage and corn ethanol the lowest. Feedstock cultivation and ethanol production were the main sources of indirect emissions, accounting for 92.2 - 93.1% of total indirect emissions, with little difference in the share of the three types of ethanol.

3.2 Distribution of Indirect Emissions of the Three Types of Ethanol In the Various Sectors of the Production Chain

Disaggregating the life-cycle indirect emissions of bioethanol into the remaining sectors of the production chain allows for targeted guidance on mitigation policies for the bioethanol producing sectors. The remaining 42 sectoral emissions calculated using the EIO-LCA are indirect emissions, and Figure 3 shows the 10 sectors with the largest indirect emissions.

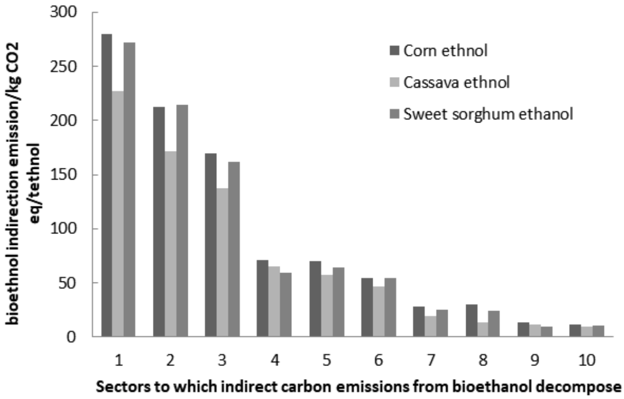

Fig. 3. Ten sectors with the highest indirect emissions in the three bioethanol categories

Note: The above ten sectors are the ten sectors with the largest indirect carbon emissions, namely. 1. electricity and heat production and supply. 2. coal mining and washing. 3. chemical raw materials and chemical products manufacturing. 4. Transport. 5. agriculture, forestry, animal husbandry, fishery and water conservancy. 6. ferrous metal smelting and rolling. 7. petroleum processing coking and nuclear fuel processing. 8. non-metallic mineral products. 9. oil and gas extraction. 10.others (including storage and post and telecommunications).

Figure 3 shows that all three types of ethanol are emitted most by the production and supply of electricity and heat, accounting for 30-32% of the total indirect emissions (mainly to provide electricity and heat for other sectors), with corn ethanol accounting for 32%. The top three sectors of emissions in the three types of ethanol are the production and supply of electricity and heat, coal mining and washing, and chemical raw materials and chemical products manufacturing, and the total indirect emissions of these three sectors account for about 73%-76% of the indirect emissions, and the sum of the emissions of the remaining sectors accounts for only about 20%, which indicates that the indirect GHG emissions of the three types of bioethanol mainly come from these three sectors, with a focus on targeting these Focusing on the production of these three sectors to formulate emission reduction policies, controlling the use of electricity, coal, fertilisers, pesticides and chemical auxiliaries can effectively reduce the indirect GHG emissions of cassava ethanol.

Comparison of the distribution of indirect carbon emissions from the three types of ethanol in the sector shows that the sectoral indirect carbon emissions from corn ethanol are higher than those from the other two types of ethanol, except for coal mining and washing, which are lower than those from sweet sorghum ethanol. One of the reasons for this is that corn ethanol as a grain ethanol is a relatively primitive process, while cassava and sweet sorghum ethanol as a 1.5 generation of non-grain ethanol production process has been optimised further, and the production policies need to be formulated for the production of corn ethanol sector. It is necessary to formulate emission reduction policies for the production of the corn ethanol sector, and to rationally control the use of fertilisers and coal and electricity. Sweet sorghum ethanol, on the other hand, has high indirect carbon emissions in both of these sectors, and the use of coal needs to be rationally controlled.

3.3 Comparison with Conventional Petrol

Comparing the life cycle carbon emission results of the three bioethanols in this study with conventional petrol, which has a carbon emission of 4.45 kgCO_2/kg, only cassava ethanol is lower than the GHG emission of conventional petrol in this study, where cassava ethanol reduces emissions by 6.1% relative to conventionalpetrol, while corn and sweet sorghum ethanol emit higher emissions than conventional petrol, which also roughly corresponds to the results of previous studies on corn and cassava ethanol, and bioethanol is indeed a green energy source in several favoured regions if only the carbon emissions during the cultivation of the raw material are considered. At the same time, the net CO_2 absorbed by photosynthesis is not considered in this paper.

4 Conclusion

Based on the results and discussions presented above, the conclusions are obtained as below:

(1) The GHG emissions of bioethanol produced from three main raw materials were calculated, with maize ethanol represented by Jilin, cassava ethanol by Guangxi, and sweet sorghum ethanol by Northwest China. The life cycle GHG emissions of the three bioethanols were calculated to be between 4183.80-4877.78 kg CO_2 eq/t ethanol, with corn ethanol having the highest emission of 4877.78 kg CO_2 eq/t ethanol, and cassava ethanol having the smallest direct carbon emission of 4183.80 kg CO_2 eq/t ethanol, and the GHG emissions of the three types of ethanol were analysed simultaneously emissions of the three types of ethanol were also analysed in terms of the proportion of each stage of emissions and the proportion of indirect and direct emissions, and the reasons for the higher proportion of each type of stage were also analysed, and targeted emission reduction proposals were put forward.

(2) The distribution of indirect carbon emissions from the three types of ethanol in various sectors of the production chain was analysed. The top three sectors in terms of emissions in the three types of ethanol are all the production and supply of electricity and heat, coal mining and washing, and the manufacturing of chemical raw materials and chemical products, and the total indirect emissions from the three sectors account for about 73%-76% of the indirect emissions.

(3) The life cycle emission results of the three types of ethanol in this paper were compared with other studies and conventional gasoline, and only cassava ethanol was found to be more emission-reducing than conventional gasoline, and the reasons for this were analysed.

References

1. Wu Y, Ma X, Wu K. (2023) The Impact of Economic Growth and Structural Changes on Carbon and Air Pollutant Emissions in Asian Countries: A Driving Force Analysis Based on KAYA, LMDI, and SDA Decomposition. J. Ecological Economic, 39 (12):191-205.
2. Barnett, Mark O. (2010) Biofuels and Greenhouse Gas Emissions: Green or Red? J. Environmental Science & Technology, 2010, 44(14):5330-1.
3. Chen D. (2023) Carbon emission assessment of cellulose ethanol lifecycle. J. Chemical and Pharmaceutical Engineering, 44(01):9-13.
4. Geng Z, Yang S, Zhang J. (2023) Life cycle assessment and carbon neutrality strategy research of cassava fuel ethanol project. J. Brewing Technology, (06) :65-70.
5. Lenzen M. (2018) Errors in Conventional and Inputm²utput—based Life—Cycle Inventories. J. Journal of Industrial Ecology, 4(4):127-148.
6. Suh S, Lenzen M, Treloar G J, et al. (2004) System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches. J. Environmental Science & Technology, 38(3):657-664.
7. Curran M A. (1996) Environmental life-cycle assessment. J. International Journal of Life Cycle Assessment, 1(3):179-179.
8. Liu C, Huang Y, Wang X, et al. (2017) Total environmental impacts of biofuels from corn stover using a hybrid life cycle assessment (LCA) model combining Process LCA and Economic Input-Output LCA. J. Integr Environ Assess Manag.
9. Kucukvar M, Tatari O. (2011) Sustainability assessment of algae cofiring in a coal-fired power plant: A hybrid LCA model. C//IEEE.IEEE.
10. Baral A, Bakshi B R. (2010) Emergy analysis using US economic input–output models with applications to life cycles of gasoline and corn ethanol. J. Ecological Modelling, 221 (15): 1807-1818.
11. Li X, Ji J, Ma X. (2011) Research on Greenhouse Gas Emissions from Fuel Ethanol Life Cycle Based on EIO-LCA. J. Journal of Peking University: Natural Science Edition, 47(6):8.
12. Melillo J M, Reilly J M, Kicklighter D W, et al. (2009) Indirect Emission from biofuels: How Important. J. 2009.
13. ISO. (1997) Environmental manage life cycle assessment principles and framework. ISO.
14. Xia X, Zhang J, Xi B. (2012) Evaluation and Policy Research of Fuel Ethanol Based on Life Cycle. M. China Environmental Science Press.
15. Hendrickson C T, Horvath A, Joshi S, et al. (1998) Economic input-output models for environmental life-cycle assessment. J Environmental Science & Technology,32(7): 184-191.
16. Hendrickson C T, Lave L B, Matthews H S. (2010) Environmental life cycle assessment of goods and services: an input-output approach. M. Routledge.
17. Joshi S. (2000) Product environmental life-cycle assessment using input-output techniques. J. Journal of Industrial Ecology, 3(2-3): 95-120.
18. Wang C, Zhang L,Pang M. (2015) A Review of Research on Life Cycle Assessment Methods——On the Development and Application of Hybrid Life Cycle Assessment J. Journal of Natural Resources, 30(07):1232-1242.