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Original research article

Potential of Using Ethanol as Fuel in the Transportation Sector

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ABSTRACT

Ethanol is considered a renewable energy source which could be blended with fossil fuels to reduce carbon dioxide emissions. Since the production of ethanol involves various processes, numerous studies have found that one of the processes significantly impacting climate change is the acquisition of raw materials. Therefore, this research will focus on calculating the carbon dioxide emissions that impact global warming from the processes of obtaining fresh and burnt sugarcane, which are the primary raw materials in the production of molasses and subsequently using molasses to produce ethanol. 1 ton of ethanol was used as a functional unit. This research was analyzed following Thailand Greenhouse Gas Management Organization (Public Organization) and the fifth Intergovernmental Panel on Climate Change report. The results illustrate that the acquisition of fresh cane has the greatest impact on carbon dioxide emissions per functional unit (kgCO_2eq/FU), accounting for 31.20% of the total. Moreover, the acquisition of burnt sugarcane has a high value at 22.29%. However, if we compared to the same quantity proportion, the emissions factor from burnt sugarcane are higher than those from fresh sugarcane due to open burning. These values were calculated based on the use of nitrogen-containing fertilizers, which account for 56.73%. This is the highest proportion in the sugarcane production process. In Thailand, the demand for renewable energy continues to rise. Therefore, this research aims to enhance the necessary database for analyzing LCA related to ethanol, as well as to find ways to minimize potential impacts as much as possible.

Keywords: Carbon footprint; Ethanol; Greenhouse gases; Molasses; Sugarcane

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1. Introduction

Ethanol is one of the types of alcohol that has been used for a long time in Thailand since 1985 [1] because it can be produced from various agricultural crops such as sugarcane, molasses, cassava, and corn. Since these plants absorb carbon dioxide gas to use in the photosynthesis process, it is considered that if these plants are grown and used, it will also reduce carbon dioxide emissions. With the advantages mentioned, ethanol can be produced almost every day of the year. The first purpose of planting sugarcane is to produce various types of sugar, or what we often call sucrose, sugarcane is planted in suitable areas spread over a wide area, resulting in high yields.

Normally, what is often obtained from sugar production is molasses, which is known as a by-product of sugar production. This molasses is a high-quality product that is often used to produce ethanol. Although when we consider the proportion of sugar in this product, it may not be equal to sugar, it is suitable and sufficient to be used to produce alcohol. Moreover, the proportion of this by-product is enough to produce a fairly large amount of ethanol, and it will be mixed with fossil fuels to reduce dependence on them, and it is often claimed to reduce carbon dioxide emissions to some extent.

Ethanol is used as an ingredient in many industries such as the perfume industry, medicine, and one of the important industries is the transportation or automotive industry. This industry mixes ethanol with diesel or gasoline in the appropriate proportion to create biodiesel and gasohol.

If ethanol is used in the right proportion, it will show that the combustion in the engine is more complete because ethanol contains oxygen. Therefore, it increases the oxygen in the system, which is a suitable representative of combustion. From the research of Elfasakhany [2], an experiment was conducted at the College of Engineering and Technology, Taibah University, Saudi Arabia. A 4-stroke Spark Ignition engine was tested with gasoline mixed with ethanol in various proportions, namely E0 (pure gasoline), E10, E15, E20, E25, and then measured the exhaust emissions, namely CO, UHC, NOx, and found that carbon monoxide (CO) emissions were significantly reduced when the proportion of ethanol in the fuel was increased. The ethanol mixture allows for more complete combustion because ethanol contains oxygen in the molecule. Moreover, the emission of unburned hydrocarbons (UHC) decreased continuously with the increased amount of ethanol due to cleaner and more complete combustion. Nitrogen oxide (NOx) emissions tended to increase slightly. In some proportions of ethanol, it is assumed that this is due to a slightly higher combustion temperature due to better combustion.

Moreover, in the research of Isam E. Yousif and Adel Mahmoud Saleh [3] from the Department of Mechanical Engineering, Baghdad University of Technology, Iraq, used LOTUS v.6.01 software to simulate a single cylinder spark ignition internal combustion engine. Different fuel blends were tested, namely E50B20 (50% ethanol, 20% butanol, 30% gasoline), E20B50 (20% ethanol, 50% butanol, 30% gasoline), E50 (50% ethanol, 50% gasoline), and B50 (50% butanol, 50% gasoline). The Olikara & Borman Equilibrium Routines were used to calculate the emissions levels. The best engine performance was found with a blend of 50% butanol and 50% gasoline (B50). The other blends (E50B20, E20B50, E50) showed acceptable performance. CO Reduction, ethanol and butanol fuel blends provide more complete combustion, resulting in significantly lower CO emissions compared to pure gasoline. UHC Reduction, high oxygen content fuels such as ethanol and butanol provide better combustion, resulting in lower UHC emissions, especially in E20B50 blends. NOx Reduction, the cooler combustion caused by the use of alcohol in fuels reduces the combustion chamber temperature, resulting in lower NOx emissions, unlike other studies where NOx may increase at high temperatures. Due to these results, all blends tested reduced CO, UHC and NOx emissions compared to using pure gasoline.

Dilip Khatiwada and Semida Silveira [4] from the Royal Institute of Technology (KTH), Sweden, assessed the life cycle greenhouse gas (GHG) balance of ethanol produced from molasses in Nepal. The study focused on a molasses-based ethanol plant in Nepal, using a high-efficiency plant as a case study, and used a life cycle assessment (LCA) approach to analyze GHG emissions throughout the ethanol production and utilization, as well as sensitivity analysis to assess the impact of changes in factors such as prices of sugar and molasses in market, the amount of nitrogen fertilizer used in sugarcane cultivation, and the yield of sugarcane per hectare. The results showed that the total carbon dioxide emissions from the production and use of ethanol produced from molasses in Nepal amounted to 432.50 kg CO_2eq per cubic meter of ethanol, or 20.40 grams CO_2eq per megajoule, compared to conventional gasoline. The use of ethanol from molasses can reduce greenhouse gas emissions by 76.60%.Sensitivity analysis shows that reducing nitrogen fertilizer use or increasing yield per rai will result in significant GHG reductions, which further emphasizes that sugarcane cultivation is the main source of GHG emissions.

Amores and colleagues [5] conducted a comprehensive environmental evaluation of ethanol derived from sugarcane in the Tucumán region of Argentina. The goal was to identify which production stages contribute most to environmental burdens, using a life cycle assessment (LCA) approach. The research focused on the sugarcane ethanol supply chain. The system boundaries included all processes from crop cultivation to ethanol production (cradle-to-gate). The study used LCA methodology following ISO standards, quantifying environmental impacts per megajoule (MJ) of fuel ethanol. Three feedstock sources were considered: sugarcane juice, molasses, and honey (a semi-processed sugar product). The analysis included agricultural inputs (fertilizers, pesticides), fuel use, and energy sources in the production chain. The results illustrated that the farming stage was the leading source of greenhouse gas (GHG) emissions, primarily due to nitrogen-based fertilizers and pre-harvest field burning. Moreover, ethanol made from molasses, a co-product of sugar production, was found to have a lower environmental impact than ethanol from sugarcane juice or honey. Besides, the use of bagasse (sugarcane fiber) as a biomass energy source during processing helped reduce fossil fuel dependency and related carbon dioxide emissions. From their recommendations, reducing the practice of pre-harvest burning in sugarcane fields would lead to a noticeable decline in overall greenhouse gas emissions associated with ethanol production. Improvements in nitrogen fertilizer management could significantly lower nitrous oxide (N_2O) emissions, which are a major contributor to the climate change impact during cultivation. So, using ethanol as part of fuel is considered an alternative energy that helps reduce carbon dioxide emissions from direct reliance on fossil fuels.

Given that many studies have demonstrated that the raw material acquisition is one of the phases which contribute the most significantly to greenhouse gas emissions, this research specifically focuses on evaluating the environmental impacts associated with the acquisition of feedstocks used in ethanol production for fuel applications. The analysis is based on both primary data collected from ethanol production facilities located in the northern region of Thailand and secondary data obtained from credible national sources. These datasets were utilized to assess GHG emissions in terms of carbon dioxide equivalents (CO_2eq), thereby providing a comprehensive understanding of the emissions associated with upstream processes in ethanol supply chains.

2. Materials and Methods

2.1 Goal and scope definition

To find the impact of ethanol production from molasses. Cradle to Gate technique, which is the evaluation from the beginning of precursors to conversion of ethanol was set.

2.2 Assessment unit

The assessment unit was kilograms of CO2eq per ton of ethanol produced (kg CO_2eq/ton ethanol).

2.3 System boundaries

The system boundaries of the raw material acquisition process consist of three main components which focus on finding the carbon dioxide emissions from each process.

First, the acquisition of primary feedstocks, which includes the consideration of both fresh sugarcane and burnt sugarcane as the initial raw materials used in the production of molasses and sugar that are subsequently processed into ethanol.

Second, the acquisition of raw water, which involves examining the sources and means by which water is obtained for use in each stage of the process.

Lastly, the acquisition of chemicals is considered, encompassing the production, utilization, and transportation of each type of chemical employed throughout the system. The detailed system boundaries for raw material acquisition are illustrated in Fig. 1.

2.4 Acquisition of data

This study employed two categories of data to support the life cycle assessment. The primary data was collected through field surveys conducted on-site using structured questionnaires.

According to the 2023/2024 sugarcane cultivation report published by the Office of the Cane and Sugar Board (OCSB) in 2024 [6], the regional distribution of sugarcane cultivation areas in Thailand—ranked from highest to lowest—is as follows: the Northeastern region, the Central region, the Northern region, and the Eastern region. Within the Northern region, Phetchabun Province ranks as the third-largest sugarcane-producing province, with a total cultivation area of approximately 522,717 rai, or about 83,635 hectares (ha).

Due to the availability and willingness of local stakeholders to provide information, combined with the province's significant share of sugarcane cultivation, Phetchabun was deemed an appropriate and representative location for conducting field surveys and collecting primary data from sugarcane farmers in this study.

The data collection was designed to

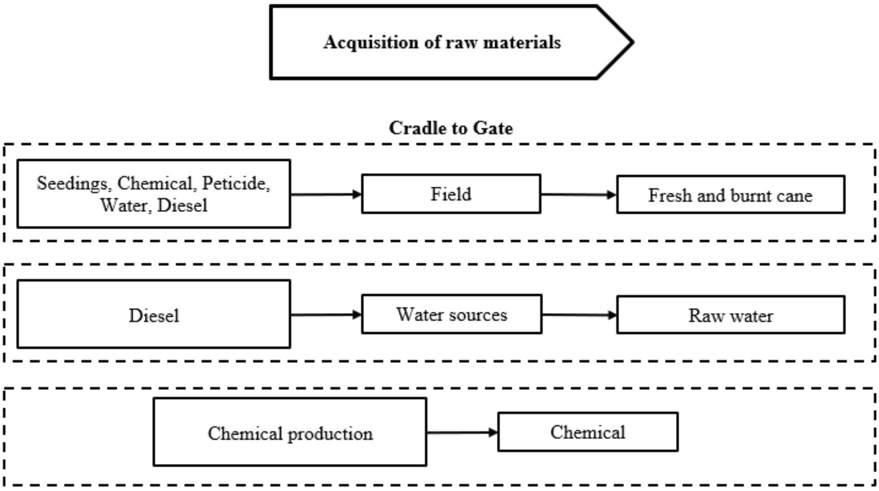

Fig. 1. The system boundaries of the raw material acquisition stage.

reflect actual agricultural as comprehensively as possible, ensuring that the inventory inputs used in the calculation are grounded in empirical observations and local operational contexts.

The secondary data used in this study were primarily derived from the report titled [7]. This document served as a critical reference for background emissions data and system boundary assumptions where primary data were unavailable or beyond the temporal or spatial scope of this research.

2.5 Questionnaire

Accurate and comprehensive data collection concerning the feedstocks used in carbon footprint assessments is critical, as it ensures the precision and credibility of the results while minimizing the risk of neglect across the supply chain. Incomplete or insufficient raw data can often lead to gaps in the analysis, reducing the reliability and scientific integrity of the study. To address this, the present research undertook a field-based primary data collection campaign across multiple sugarcane-growing regions in Thailand. The survey encompassed a broad spectrum of farm sizes—categorized as small, medium, and large-scale operations—and involved direct engagement with farmers through structured questionnaires, administered with their consent. These instruments were designed to capture comprehensive and consistent datasets from real farming practices, under 3 sections; General Information, Input Factors Used and Harvesting/Transportation.

The first part of the questionnaire focused on general background information, such as the geographical location of each farm, total cultivated land area under sugarcane, and, where permitted, the recording of GPS coordinates. These geolocations were collected with the intention of supporting future analyses on land use change (LUC), particularly if such assessments are incorporated into subsequent environmental studies.

The second section of the questionnaire was structured into three technical sub-sections reflecting key stages of sugarcane cultivation. The first sub-section, dedicated to land preparation, collected data on pre-planting practices such as whether soil tillage or furrowing was conducted, whether mechanized equipment was utilized, the specific type and quantity of fuel consumed by such machinery, and details on the types and quantities of basal fertilizers (soil-enhancing inputs) applied. Additionally, respondents were asked to specify the number of fertilizer applications performed per planting cycle.

The second sub-section focused on the planting stage, including the length of the planting-harvest cycle, the spacing between planted cane rows or stalks, and the methodology of planting—whether by manual labor or mechanical planting equipment. This section also aimed to determine the labor intensity or degree of mechanization employed in the planting process.

The third sub-section addressed crop maintenance, particularly the fertilization strategy used to ensure healthy crop development and to optimize sucrose content. Farmers were requested to specify the types of fertilizers used for crop nutrition, the amount of fertilizer applied per application, and the number of applications conducted throughout the growing period.

The final section of the questionnaire was dedicated to harvesting and transportation. It gathered quantitative data on actual yield (harvested cane per land area) and qualitative information on harvesting methods. For operations utilizing harvesting machinery, the type and amount of fuel used were recorded. This section also included questions about post-harvest field management, specifically the handling of crop residues and agricultural by-products such as cane leaves and tops. This information was essential for assessing the carbon dioxide emissions resulting from biomass decomposition or open burning, which are common practices in certain regions.

Furthermore, the transportation component of this section was comprehensive. It included the logistics of sugarcane sets (planting materials) from source to farm, transport of harvested cane to sugar mills, and the delivery of agro-inputs, such as fertilizers and chemicals, to the fields. For each transportation route, data were collected on travel distance, type of vehicle, and estimated or measured fuel consumption. The final part of the questionnaire provided space for open-ended feedback, allowing participating farmers to share any additional insights, recommendations, or context-specific practices that they deemed relevant for the purposes of this research or for guiding future studies.

2.6 Allocation method

Mass allocation is a method used in carbon footprint analysis to distribute environmental impacts among multiple products or co-products from a single process based on their mass (weight).

It is commonly applied when a production process generates one main product and one or more co-products (e.g., sugar and molasses from sugarcane milling). The co-products have different uses, and no clear economic hierarchy

In the conventional sugar production process, a total of six sugar products are typically generated, alongside molasses, which is produced as a by-product. However, in the context of this study, the focus is specifically placed on molasses, as it is the selected feedstock for ethanol production. Therefore, a methodological adjustment was made to treat molasses as the primary product of interest, while the six types of sugar were reclassified as co-products. The allocation process was conducted based on the mass of sucrose contained in each product, which is generally represented by the sucrose content or %Pol in the final products.

In practice, all types of sugar products contain approximately 99.30% Pol, whereas molasses contain approximately 26.25% Pol. These %Pol values were multiplied by the actual mass of each respective product to determine the total quantity of sucrose attributed to each product stream. The allocation was subsequently performed according to these sucrose-based quantities, resulting in a calculated allocation factor of 10.73% assigned to molasses within the context of this study.

As for the ethanol production process, no allocation was deemed necessary. This is because each subprocess within the ethanol production system yields a single output with no co-products or by-products generated at any stage.

2.7 Emission factor

An Emission Factor (EF) is a representative value that quantifies the average amount of a specific pollutant—typically expressed in mass units (e.g., kg or g)—emitted to the atmosphere per unit of activity or input/output. For instance, EF may be defined as kilograms of CO_2 emitted per liter of diesel combusted or per kilogram of fertilizer applied. In addition, sources of emission factors can be obtained from a variety of authoritative sources, including international guidelines and databases and national databases. For example, Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories, United States Environmental Protection Agency (U.S. EPA), and European Environment Agency (EEA) are grouped by international guidelines. Another group consists of Thailand Greenhouse Gas Management Organization (Public organization) (TGO), Peer-reviewed scientific literature, and Site-specific measurements in the case of primary data collection or experimental studies. Emission factors play a fundamental role in environmental assessments, particularly in situations where direct emission measurements are not feasible.

They are extensively utilized as essential inputs in various analytical frameworks, including life cycle assessment (LCA) for quantifying emissions throughout the life cycle of a product or process, carbon footprint analysis, and environmental impact assessments (EIA). Additionally, emission factors are integral to the development of greenhouse gas inventories and reporting systems, especially in the context of compliance with international agreements such as the Paris Agreement. Furthermore, they serve as a basis for policy development and the formulation of environmental regulations.

The calculation of fertilizer acquisition in this study is based on the constituent materials used in base fertilizer production. Data were primarily obtained from the C to G database, which provides inventory data specific to fertilizer manufacturing in Thailand. For nitrogen (N) input, urea is commonly used as the primary blending component, containing 46% nitrogen by weight. For phosphorus (P), diammonium phosphate (DAP) is the most widely used source, which contains 18% nitrogen and 46% phosphorus. Potassium (K) is typically supplied through the use of potassium chloride, which contains 60% potassium. It is important to note that phosphorus content in fertilizers is considered in the form of P_2O_5 , while potassium content is expressed as K_2O. the Table 1. illustrated the examples of EF for upstream fertilizer production. In addition, the TGO suggested that

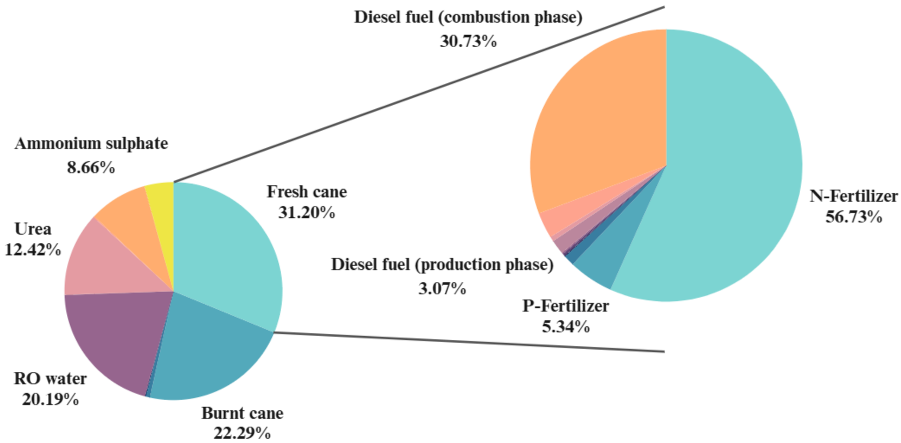

Fig. 2. A pie chart illustrates GHG Emission Contributions from Raw Material Acquisition Phase.

Table 1. Examples of EF for upstream fertilizer production.

Fertilizer Source	Emission Factor (EF)
Urea	3.3036 kg CO_2 eq/kg N
DAP	1.5716 kg CO_2 eq/kg P
Potassium chloride	0.4974 kg CO_2 eq/kg K
Filler (assumed)	0 kg CO_2 eq (assumed EF = 0)

when the nitrogen fertilizer was used, it also released nitrous oxide equal to percentage of nitrogen in the fertilizer usage multiplied with the molecular weight of carbon dioxide and divided with the molecular weight of nitrous oxide and then multiplied with 265 (GWP values for 100-year time horizon).

2.8 GHG emissions calculation

To calculate greenhouse gas (GHG) emissions, the first step involves identifying the emission factors (EFs) of each relevant component that contributes to environmental impacts. These emission factors are then used to convert activity data into carbon dioxide equivalent (CO_2eq) emissions. Following this, emissions from the transportation sector must be assessed. This includes data such as the distance between the cultivation site and the sugar mill, the load per transport round, and the emission factors associated with each type of vehicle or tractor used.

After calculating transportation-related emissions and converting them into CO_2 equivalents, the resulting values are added to the GHG emissions from upstream processes. This comprehensive approach allows for the estimation of total GHG emissions across all stages of the system boundary under consideration. The table below presents the calculations of greenhouse gas (GHG) emissions for cultivation process under consideration.

3. Results and Discussion

The results of this study indicate that the total greenhouse gas (GHG) emissions from acquisition phase amount to 52.39 kg CO_2 equivalent per ton of ethanol produced.

The proportion of carbon dioxide emissions is illustrated in Fig. 2, about 31.20% and 22.29% of emissions originated from the acquisition of fresh sugarcane and burnt sugarcane, respectively. These two components together represented more than half of the total emissions from raw material acquisition, indicating that sugarcane cultivation is the dominant contributor.

A closer analysis revealed that approximately 56.73% of these emissions from cane acquisition (Tables 2-3) were directly linked to the production and application of nitrogen fertilizers, particularly those synthesized from urea. According to the Urease Test Protocol by Benita Brink [8], the underlying biochemical mechanism can be explained by the reaction where urea reacts with water and is hydrolyzed by the enzyme urease, releasing carbon dioxide and ammonia as byproducts. This reaction demonstrates that urea-based fertilizers are a direct source of carbon dioxide emissions upon decomposition in the field. Moreover, according to the Thailand Greenhouse Gas Management Organization (TGO), it is reported that approximately 1% of the applied nitrogen is converted into nitrous oxide (N_2O), a greenhouse gas with a global warming potential (GWP) that is 265 times greater than that of carbon dioxide. This combination of direct CO_2 emissions and potent N_2O emissions clearly explain why the use of nitrogen fertilizers accounts for more than half of the GHG emissions in this stage.

One promising mitigation strategy for reducing emissions in this stage is to substitute synthetic nitrogen fertilizers with organic alternatives such as manure. Field data revealed that the average rate of chemical fertilizer application was 0.91 sacks per rai, whereas plots that also received chicken manure exhibited a reduced chemical fertilizer rate of 0.87 sacks per rai. This translates to a reduction of 0.04 sacks per rai, or 4 sacks per 100 rai, highlighting the potential for reducing synthetic fertilizer dependence when manure is co-applied. This substitution also results in lower emissions, as the emission factor (EF) for chicken manure is approximately 0.197 kg CO_2 eq per functional unit (FU), compared to a significantly higher EF of 7.9865 kg CO_2 eq/FU for nitrogen-based fertilizers alone, according to TGO.

Beyond nitrogen fertilizers, other notable emission sources in this stage include the production of reverse osmosis (RO) water, which is mainly required in steam generation and other supporting processes.

4. Conclusion

This research was conducted with the objective of assessing the carbon footprint or the greenhouse gas (GHG) emissions from acquisition phase associated with the production of 1 ton of ethanol. The mass allocation method based on sucrose content was applied, and the environmental impacts were calculated from relevant raw material in acquisition step. For the acquisition of molasses, all data were collected through primary sources, including field visits, interviews with farmers, and related personnel. The ethanol production process from molasses utilized secondary data obtained entirely from environmental organizations in Thailand.

The findings revealed that acquisition phase release carbon dioxide emission equal 52.39 kg CO_2 equivalent per ton of ethanol produced. Within this phase, emissions were mainly from the acquisition of fresh sugarcane (31.20%), burnt sugarcane (22.29%), RO water production (20.19%), urea usage (8.66%), and other sources which together contributed 17.66%.

This study primarily focused on the calculation of raw material acquisition for the production of one ton of ethanol, with the objective of utilizing the resulting ethanol as a blended component in transportation fuels. The target applications are not limited to conventional vehicles such as automobiles and motorcycles but ex-

Table 2. The calculations of EF for fresh cane acquisition.

List	Unit	Input Quantity/ FU	Emission Factor ($kgCO_2eq/FU$)	CO_2 Emission (excluded transporta-tion), (kg CO_2eq)1*	Distance (km)	Transport Load-Outbound (km), 2*	Transport Load-Return (km), 3*	% Outbound	% Return
Input									
water	m^3	0.003082	-	-					
N-Fertilizer	kg	0.001144	7.9865	0.008541	-	-	-	-	-
P-Fertilizer	kg	0.000511	1.5716	0.000804	10	1.14E-05	1.63E-06	100	0
K-Fertilizer	kg	0.000388	0.4974	0.000193	10	5.11E-06	7.31E-07	100	0
Chicken manure	kg	0.000021	0.1097	0.000002	10	3.88E-06	5.54E-07	100	0
2,4-D and 2,4-D mixtures with other active ingredients	kg	0.000001	8.51	0.00001	10	2.07E-07	2.96E-08	100	0
Glufosinate with others	kg	0.000008	5.01	0.000042	10	1.17E-08	1.67E-09	100	0
Cytron and Cytron with others	kg	0.000003	8.51	0.000024	10	8.43E-08	1.20E-08	100	0
Dasaflo and Dasaflo with others	kg	0.000031	8.51	0.000264	10	2.85E-08	4.07E-09	100	0
Diuron and Diuron with others	kg	0.00001	8.51	0.000086	10	3.10E-07	4.42E-08	100	0
Diesel fuel (production phase)	kg	0.001305	0.3522	0.000459	10	1.01E-07	1.44E-08	100	0
Diesel fuel (combustion phase)	kg	0.001553	2.9793	0.004627	10	1.31E-05	1.86E-06	100	0
Output					10	1.14E-05	1.63E-06	100	0
Fresh cane	kg	1	-	-					
			Total	0.0150515	-	-	-	-	-

- EF was taken from TGO CFP document in July 2022.
- The vehicle type is a 4-wheel small truck, max payload 7 tons (100% loaded outbound, 0% return load).
- Transport Load – Outbound (2*) is calculated from quantity/FU multiplied with distance and divided by 1000.
- Transport Load – Return (3*) is calculated from 2* divided by 7 tons.

tend to aviation fuels as well. In this context, the consideration of raw material acquisition can be likened to the headwaters of a river, from which every subsequent process must be assessed in a stepwise manner—ultimately extending to the blending of ethanol into fuel for transportation or even to the combustion of such fuels.

In the future, if primary data can be obtained for each stage of the supply chain, the overall calculation will become significantly more comprehensive and accurate. It is anticipated that this research will contribute to and support the advancement of further studies in the transportation sector in Thailand. Moreover, this study has not yet accounted for land use change (LUC), which is a critical component in life cycle assessments. Therefore, it is strongly recommended that future research incorporates geographic coordinate data of cultivation areas in order to calculate land use

Table 3. The calculations of EF for fresh cane acquisition (continued).

List	EF Outbound ($kgCO_2eq$/ tkm), 4*	EF Return ($kgCO_2$ eq/tkm), 5*	Transport Emissions ($kgCO_2eq$) 6*	Total Emissions ($kgCO_2eq$) 1* + 6*	Total Emissions ($kgCO_2eq$) 1* + 6*	Proportion of Total Emission (%)
Input					-	56.73
water	-	-	-	-	-	5.34
N-Fertilizer	0.1411	0.3131	2.13E-06	8.54E-03	8.54E-03	1.29
P-Fertilizer	0.1411	0.3131	9.50E-07	8.05E-04	8.05E-04	0.02
K-Fertilizer	0.1411	0.3131	7.21E-07	1.94E-04	1.94E-04	0.07
Chicken manure	0.1411	0.3131	3.84E-08	2.31E-06	2.31E-06	0.28
2,4-D and 2,4-D mixtures with other active ingredients	0.1411	0.3131	2.17E-09	9.96E-06	9.96E-06	0.16
Glufosinate with others	0.1411	0.3131	1.57E-08	4.22E-05	4.22E-05	1.75
Cytron and Cytron with others	0.1411	0.3131	5.30E-09	2.43E-05	2.43E-05	0.57
Dasaflo and Dasaflo with others	0.1411	0.3131	5.76E-08	2.64E-04	2.64E-04	3.07
Diuron and Diuron with others	0.1411	0.3131	1.87E-08	8.56E-05	8.56E-05	30.73
Diesel fuel (production phase)	0.1411	0.3131	2.42E-06	4.62E-04	4.62E-04	56.73
Diesel fuel (combustion phase)	0.1411	0.3131	2.13E-06	4.63E-03	4.63E-03	5.34
Output						1.29
Fresh cane	1					0.02
	Total		6.36E-06			100
The carbon footprint for producing 1 kilogram of fresh sugarcane is estimated to be				0.0150578		

- 4* and 5* were taken from TGO guideline book for 4-wheel small truck with max payload 7-ton load.
- 6* = (2* × 4*) + (3* × 5*)

change using geospatial tools. Incorporating these aspects will enhance the precision of the analysis and provide a stronger foundation for demonstrating the sustainability and appropriateness of ethanol as a blended fuel component across multiple transportation sectors.

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Appendix

Table 4. The calculations of EF for RO water.

List	Unit	Input Quantity/FU	Emission Factor ($kgCO_2$ eq/FU)	CO_2 Emission (excluded transportation), ($kgCO_2$ eq) 1*	Distance (km)	Transport Load-Outbound (km), 2*	Transport Load-Return (km), 3*
Input							
Softener water	L	1.705513	0.0003	0.0005	-	-	-
Sodium metabisulfite	kg	0.000004	0.47	1.70E-06	700	2.53E-06	7.91E-08
Antiscalant	kg	0.000003	1.41	4.08E-06	700	2.02E-06	6.33E-08
Biocide	kg	0.000004	1.0548	4.58E-06	700	3.04E-06	9.49E-08
Self-generated electricity	kWh	0.000824	0.0143	1.18E-05	-	-	-
Electricity from the Provincial Electricity Authority (PEA)	kWh	0.00002	0.5986	1.21E-05	-	-	-
Output							
RO water	L	1	-	-	-	-	-
Reject water	L	0.705513	-	-	-	-	-
			Total	0.0005293			

- The vehicle type is a 18-wheel truck, max payload 32 tons (100% loaded outbound, 0% return load).
- Transport Load – Outbound (2*) is calculated from quantity/FU multiplied with distance and divided by 1000.
- Transport Load – Return (3*) is calculated from 2* divided by 32 tons.

Table 5. The calculations of EF for RO water (continued).

List	% Outbound	% Return	EF Outbound $kgCO_2$ eq/tkm), 4*	EF Return ($kgCO_2$ eq/tkm), 5*	Transport Emissions ($kgCO_2$ eq) 6*	Total Emissions ($kgCO_2$ eq) 1* + 6*	EF value (kg CO_2 eq/FU)	Source of EF
Input								
Softener water	-	-	-	-	-	0.0005	0.0003	Site visiting
Sodium metabisulfite	100	0	0.0443	0.8684	1.81E-07	1.88E-06	0.47	[9]
Antiscalant	100	0	0.0443	0.8684	1.45E-07	4.22E-06	1.41	Ecoinvent 2.2, IPCC 2007
Biocide	100	0	0.0443	0.8684	2.17E-07	4.79E-06	1.0548	TGO CFP EF, July 2022, Entry 621.
Self-generated electricity	-	-	-	-	-	0.000012	0.0143	Site visiting
Electricity from the Provincial Electricity Authority (PEA)	-	-	-	-	-	0.000012	0.5986	TGO CFP EF, July 2022, Entry 59.
Output								
RO water	-	-	-	-	-	-		
Reject water	-	-	-	-	-	-		
				Total	5.42E-07			
The carbon footprint for producing 1 liter of RO water is estimated to be						0.0005298		

- 4* and 5* were taken from TGO guideline book for 18-wheel truck with max payload 32-ton load.
- 6* = (2* × 4*) + (3* × 5*).

Table 6. The EFs for acquisition of raw materials.

List	EF value (kg CO_2 eq/FU)	Source of EF
1. Cane extraction		
Fresh cane	0.0157	Calculation
Burnt cane	0.0249	(1.084 × EF of fresh cane) + 0.0079*
2. Boiling/Simmering/Blending sugar and molasses		
Lime	1.0215	TGO CFP EF, July 2022, Entry 601. Lime
Flocculant clarifier	5.35	Anionic polymer (WWT), Ecoinvent 2.0
Enzyme	1.15	[10]
Anti-scale solution	1.41	Acrylic acid, Ecoinvent 2.2, IPCC 2007
3. Dilution		
RO water	0.0005	Calculation
4. Fermentation		
Yeast	0.49	[10]
Urea	3.2826	TGO CFP EF, July 2022, Entry 651.
Phosphoric acid	1.4067	TGO CFP EF, July 2022, Entry 659.
Ammonium sulphate	2.66	Ecoinvent 2.2, IPCC 2007
Diammonium phosphate	1.5716	TGO CFP EF, July 2022, Entry 712.
Sulfuric acid	0.1219	TGO CFP EF, July 2022, Entry 650.

* Equation was taken from Product Category Rules for Sugarcane and Sugar Products from TGO.

Table 7. The input and output of raw materials in cultivation process.

List	Unit	Quantity/FU
Input		
Water	m^3	0.003082
N-Fertilizer	kg	0.001144
P-Fertilizer	kg	0.000511
K-Fertilizer	kg	0.000388
Chicken manure	kg	0.000021
2,4-D and 2,4-D mixtures with other active ingredients	kg	0.000001
Glufosinate with others	kg	0.000008
Cytron and Cytron with others	kg	0.000003
Dasaflo and Dasaflo with others	kg	0.000031
Diuron and Diuron with others	kg	0.000010
Diesel fuel (production phase)	kg	0.001305
Diesel fuel (combustion phase)	kg	0.001553
Output		
Fresh cane	kg	1

Table 8. The input of raw materials in acquisition process.

List	Unit	Quantity/FU
1. Cane extraction		
Fresh cane	kg	9,255.96
Burnt cane	kg	4,110.78
Hot water	L	4,545.11
2. Boiling/Simmering/Blending sugar and molasses		
Lime	kg	2.61
Flocculant clarifier	kg	0.10
Enzyme	kg	0.002
Anti-scale solution	kg	0.11
3. Dilution		
Molasses	kg	642.28
RO water	L	18,274.11
4. Fermentation		
Diluted molasses	kg	18,916.39
Yeast	kg	0.04
Urea	kg	1.81
Phosphoric acid	kg	0.05
Ammonium sulphate	kg	1.56
Diammonium phosphate	kg	0.01
Sulfuric acid	kg	16.79
5. Distillation		
Alcohol	kg	18,819.88
6. Dehydration		
Alcohol 95%	kg	4,187.46

Table 9. GHG emissions calculation.

List	Unit	Quantity/FU	EF value (kg CO_2 eq/FU)	Allocation value	CO2 emissions ($kgCO_2eq/FU$)	CO2 emissions ($kgCO_2eq/FU$)	Percentage of CO_2 emissions
1. Cane extraction							
Fresh cane	kg	9,255.96	0.0151	10.73%	14.9611	14.9611	31.20%
Burnt cane	kg	4,110.78	0.0242	10.73%	10.6888	10.6888	22.29%
Hot water	L	4,545.11	-	10.73%	-	-	-
2. Boiling/Simmering/Blending sugar and molasses							
Lime	kg	2.61	1.0215	100.00%	0.2866	0.2866	0.60%
Flocculant clarifier	kg	0.1	5.35	100.00%	0.0566	0.0566	0.12%
Enzyme	kg	0.002	1.15	100.00%	0.0003	0.0003	0.00%
Anti-scale solution	kg	0.11	1.41	100.00%	0.0169	0.0169	0.04%
3. Dilution							
Molasses	kg	642.28	-	-	-	-	-
RO water	L	18,274.11	0.0005	100.00%	9.6825	9.6825	20.19%
4. Fermentation							
Diluted molasses	kg	18,916.39	-	-	-	-	-
Yeast	kg	0.04	0.49	100.00%	0.0187	0.0187	0.04%
Urea	kg	1.81	3.2826	100.00%	5.957	5.957	12.42%
Phosphoric acid	kg	0.05	1.4067	100.00%	0.0714	0.0714	0.15%
Ammonium sulphate	kg	1.56	2.66	100.00%	4.152	4.152	8.66%
Diammonium phosphate	kg	0.01	1.5716	100.00%	0.0199	0.0199	0.04%
Sulfuric acid	kg	16.79	0.1219	100.00%	2.0466	2.0466	4.27%
5. Distillation							
Alcohol	kg	18,819.88	-	-			-
6. Dehydration							
Alcohol 95%	kg	4,187.46	-	-			-
				Total	47.9585	47.9585	100%

Table 10. GHG emissions calculation for transportation sector.

List	Quantity/FU	Weighted average distance (km)	EF Outbound ($kgCO_2eq/tkm$),	EF Return ($kgCO_2eq/tkm$),	Vehicle type	% O
1. Cane extraction						
Fresh and Burnt cane	13,366.74	34.25	457.84	28.61	10-wheel cargo truck with a maximum load capacity of 16 tons.	
2. Boiling/Simmering/Blending sugar and molasses						
Lime	2.61	174	0.45	0.01	18-wheel semi-trailer truck with a maximum load capacity of 32 tons (100% loading on the outbound trip, 0% loading on the return trip)	
Flocculant clarifier	0.1	298	0.03	0.00092		
Enzyme	0	289	0.0006	0.00002		
Anti-scale solution	0.11	289	0.03	0.00101		