ASSESSMENT OF THE SUBSTITUTION OF FOSSIL FUELS BY BIOFUELS IN THE TRANSPORT SECTOR IN COLOMBIA

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ABSTRACT

Based on the energy demand for fuels for the transport sector in Colombia, this study analyzed a scenario for replacing diesel with palm oil biodiesel, gasoline with sugar cane ethanol, aviation fuel with palm oil SAF and natural gas with sewage and vinasse treatment biogas. The results showed a reduction in CO_2 emissions, circular economy and excellent gains from replacing these fuels.

Keywords: Biofuels; Colombia; Biomass; Economic Analysis; CO_2 Emissions.

INTRODUCTION

In recent decades, the production and use of biofuels have been important strategies for combating climate change and helping with decarbonization of the world economy. This trend towards the use of biofuels was ratified at the most recent dialogue between governments, COP28, with the support of the Global Biofuels Alliance [1]. Colombia has collected these experiences and applied them to national policies and programs, such as the biofuel blend mandates (E5/B10) for 2023, but its progress in replacing fossil fuels is not comparable to that of the US and Brazil [2,3]. Regarding the biofuels market, biodiesel and ethanol continue to be the focus, due to oil palm and sugar ago-industrial sectors. On the other hand, alternatives for aviation fuel (jet-fuel) and natural gas are little discussed.

However, studies showed the feasibility to produce biomethane and sustainable aviation fuel (SAF) from existing biomass in Colombia, such as Andrade Morales et al. [4], who estimated the potential for biomethane production from landfills and Pipitone et al. [5], who analyzed the production of SAF and co-products from oil palm. Considering these facts, this study analyzed and quantified the biomass needed, the emissions avoided and produced, the production costs and the financial viability for a scenario of total substitution of diesel, gasoline, natural gas and aviation fuel used in the transport sector by biodiesel, ethanol, biomethane and SAF, respectively.

METHODOLOGY

Data Collection: The substitution was made on an energy basis, as shown in **Eq. (1)**, so that the consumption of fossil fuels was required. To do this, Colombian government sources and agencies were consulted, such as UPME [6] for find out the consumption of diesel and gasoline in 2023 and SICOM [7] for obtain information on the consumption of natural gas and jet-fuel consumption in 2022. In addition, the lower heating and density values were researched and summarized in the **Table 1** to represent the fuel and biofuel produced in Colombia, except for SAF.

$$\mathrm{LHV_{fossil}} * \mathrm{m_{fossil}} = \mathrm{LHV_{biofuel}} * \mathrm{m_{biofuel}} \qquad \textit{Eq. } (1)$$

For the study, the market costs of a ton of sugarcane and Fresh Fruit Bunches (FFB) of palm oil were researched, as well as the sales prices of biofuels on the Colombian market. For biomethane, the price was estimated based on the price of natural gas, considering the energy content, since there is no sales market. Finally, SAF price was adjusted to the international standard. These costs are summarized in **Appendix A.**

Table 1. Characteristics of the fuels and biofuels in Colombia.

Fuel	Density	LHV	Biofuel	Density	LHV
Diesel [8]	852	42.41	Biodiesel [8]	875	37.90
Gasoline [8]	740	45.33	Ethanol [8]	820	22.48
Natural gas @0°C [8]	0.58	39.49	Biomethane @0°C [4]	0.72	40.85
Jet-fuel [8]	826	35.58	SAF [9]	804	42.80

Density units**: kg/m³**; LHV units: **MJ/kg**

Analysis of biofuel production: The mass balance for biodiesel and ethanol production was calculated according to Canabarro et al. [10] and the biomass required was estimated. For the efficiency of biomethane production from sewage, the study by Silvio dos Santos et al. [11] was used and biomethane production from vinasse was carried out according to Stocco Baldacin [12]. Finally, the production of SAF was carried out according to Martinez et al. [13], who used oil palm as a feedstock. This study considered the co-production of some elements with commercial value, such as sugar and kernel oil during the production of ethanol and biodiesel, respectively. The same way, naphtha, diesel and propane were considered co-products of the production of SAF. In the **Appendix A** was summarized the mass balances for biofuel production. Finally, biomethane production was limited to the amount of sewage produced by half of Colombian population and the vinasse produced during the ethanol production process to replace gasoline demand.

Environmental and Economic Analysis: Production costs were estimated on the total price of the feedstock, since these costs represent 70% of the production costs. The financial viability of biofuel production was analyzed using **Eqs. (2-4)**, and the prices of co-products are listed in **Appendix A**.

$$\text{Production cost(USD\$)} = 1.30 * \left(\text{Price}\left(\frac{\text{USD\$}}{\text{ton}}\right) * \text{Feedstock(ton)}\right) \quad \text{Eq. (2)}$$

$$\text{Revenue (USD\$)} = \sum\left(\text{Price}\left(\frac{\text{USD\$}}{\text{ton}}\right) * \text{Products(ton)}\right) \quad \text{Eq. (3)}$$

$$\text{Net Income (USD\$)} = \text{Revenue (USD\$)} - \text{Production cost(USD\$)} \quad \text{Eq. (4)}$$

Environmental analysis compared the CO_2 emissions released during the crops cultivation to produce biofuels and CO_2 emissions avoided by the removal of fossil fuels in the transport sector. The CO2 emissions from biomass and fossil fuels were quantified using **Eq. (5)**, the emission factors **(f)** are listed in **Appendix A**. In addition, these emission factors considered the carbon footprint of fertilization and agrochemicals used in the production of a ton of crude palm oil and a ton of sugarcane.

$$\text{Total Emissions (tonCO}_2\text{)} = \text{f}\left(\frac{\text{tonCO}_2}{\text{ton}}\right) * \text{Source(ton)} \quad \text{Eq. (5)}$$

RESULTS AND DISCUSSION

The estimated production of biofuels to replace the fossil fuels used in the transportation sector in Colombia is shown in **Fig 1.** Current biofuel production is 10.63%, 2.38% and 0.13% of the estimated demand for biodiesel, ethanol and biomethane, respectively. The results in **Fig 2.** show the cash flow for biofuel production, the revenues are divided into sales of biodiesel (91.97%) and oil kernel (8.03%) oil kernel, sales of ethanol (29.55%) and sugar (70.45%), sales of sewage biomethane (18.05%) and vinasse (81.94%), sales of SAF (62.35%), kernel oil (7.07%), naphtha (7.49%), diesel (11.02%) and propane (12.05%). Feedstock costs represent a 44.19%, 57.48% and 150.86% of the income from biodiesel, SAF and ethanol sales, respectively. **Fig 3.** shows that one ton of CO_2 released in the feedstocks production for biodiesel, ethanol and SAF prevents the release of 3.25, 2.95 and 1.68 tons of CO_2 ton, respectively, if substitution is made. In Colombia around 0.50 million of hectares of oil palm were cultivated in 2023, which represents only 30.86% by mass of the plantations that could supply the diesel demand. These oil palm plantations should produce 1.99 million tons of biodiesel if they were destined exclusively for biodiesel production, which is not the case, as shown in **Fig 1.**

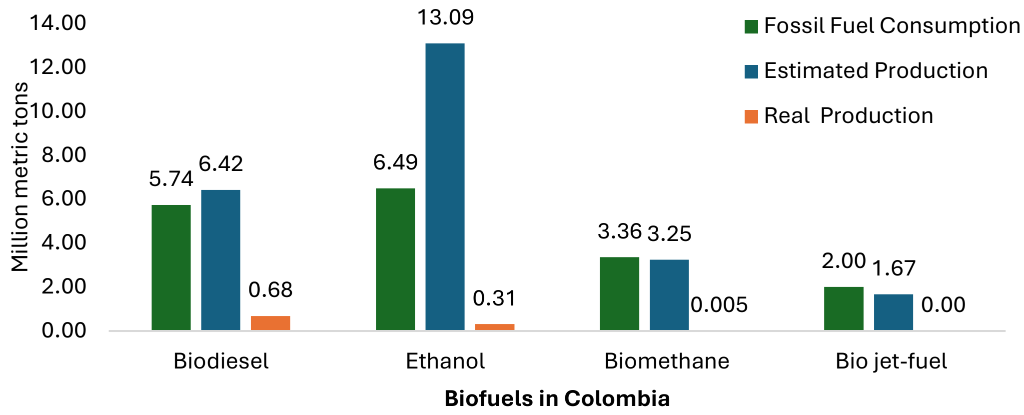

Figure 1. Fuel consumption and estimated biofuel production in Colombia.

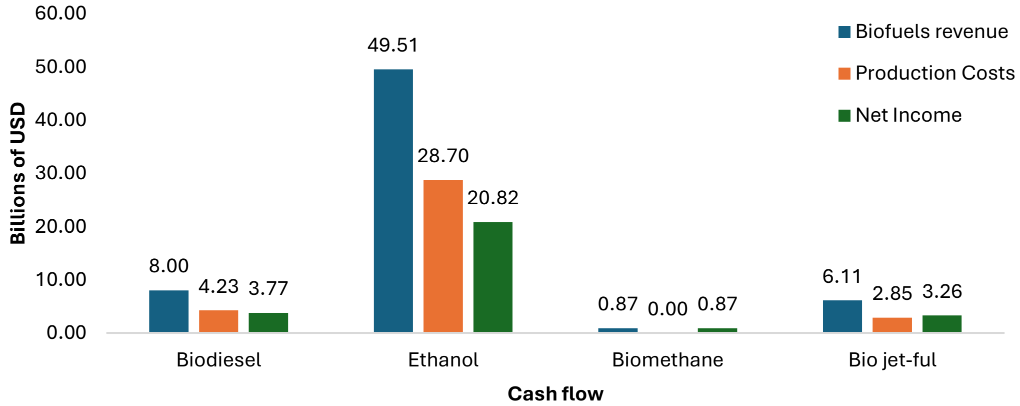

Figure 2. Economic analysis for the biofuel production in Colombia.

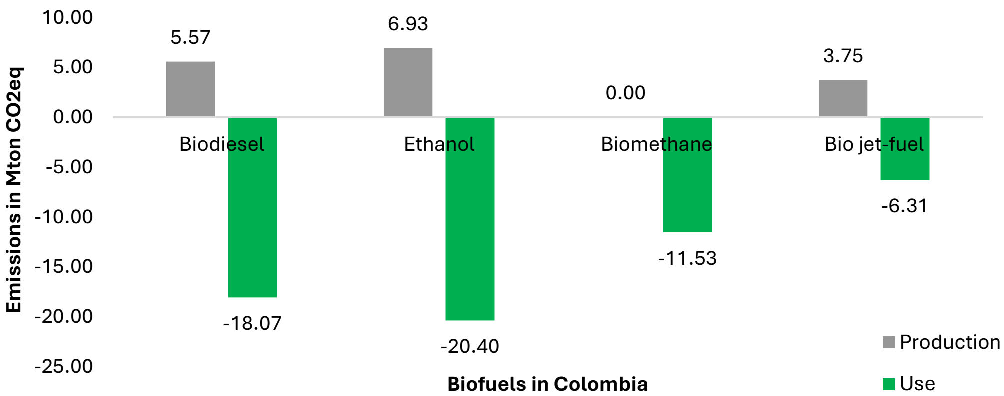

Figure 3. CO_2 emissions in the biofuel production chain in Colombia.

CONCLUSION

This study shows that 22.25 % of natural gas demand can be supplied from biomethane from sewage (4.02%) and vinasse (18.23%). The economics profits of biofuel production were identified through positive net income. In Colombia, the current ethanol production scenario is strongly associated with high sugar production, since there is no dedicated distillery. In addition, the information analyzed for biodiesel in 2023 shows that only 34.34% of oil palm plantations in Colombia were destined for biodiesel production, the rest was destinated for export and domestic oil. For the SAF and biodiesel production, it is estimated that 2.71 million hectares of oil palm are needed.

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APPENDIX A

Conversion factors: 1 Gallon = 3.785 Liters; 1 Calorie = 4.184 Joules; 1 United States Dollar (USD) = 4287 Colombian Pesos (COP)

Table 2. Market costs of feedstock and biofuels in Colombia.

Fuel	Sales Prices	BioFuel	Feedstock	Sales Prices
Diesel	692	Biodiesel	104.10	1146
Gasoline	1245	Ethanol	32.19	1118
Natural gas	890	Biomethane	0.00	1202
Jet-fuel	854	SAF	104.10	2228

Price of feedstock and fuels: **USD$/ton**

Table A. Mass balances for the biofuel production in Colombia.

Input	Output	Input	Output
1 FFB	0.214 Crude Palm Oil 0.020 Kernel Oil	0.206 Refined Palm Oil	0.206 ton Biodiesel
1 Sugarcane	0.063 Melasses 0.048 Refined Sugar 0.045 White Sugar	0.063 Melasses	0.019 Ethanol
1 Sewage*	0.249 Biogas*	0.249 Biogas*	0.149 Biomethane*
1 Ethanol*	10 Vinasse*	1 Vinasse*	5.18 Biomethane*
1 FFB	0.214 Crude Palm Oil 0.020 Kernel Oil	0.206 Refined Palm Oil	0.079 SAF 0.033 Naphtha 0.046 Diesel 0.024 Propane

Mass units: **ton; ***Units: **m³**

Table B. Market costs of co-products in biorefinery.

Products	Sales Prices
Kernel Oil	1028
Sugar	547
Naphtha	658
Diesel	692
Propane	1481

Emission factor: **USD/ton**

Table C. CO_2 emissions for a ton of biomass and several fossil fuels in Colombia.

Fuel	Emision Factors	Feedstock	Emision Factors
Diesel	3.147	Oil Palm	0.866
Gasoline	3.142	Sugarcane	0.010
Natural gas	3.432	-	-
Jet-fuel	3.147	Oil Palm	0.866

Emission factor: **tonCO_2/ton**