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Carbon Footprint of the Recent Bioenergy Crop Sugarcane Transition in Bolivia and Outlook to 2028

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Bolivia's biofuel policy has made progress in replacing gasoline imports and reducing greenhouse gas (GHG) emissions. Advances in crop yield, energy use, and fertilizer/chemical use increased the operational efficiency and reduced GHG emission potential of Bolivia's sugarcane bioenergy crop. This study examines GHG emissions resulting from sugarcane energy crop development in Bolivia. A carbon intensity inventory was compiled for 2022/2023 looking at the 2028 harvest season. Information was collected from sugarcane farmers (in the form of personal reports) and from government reports. Uncertainty and sensitivity analyses were considered during the data study. System boundaries include agricultural practice and crop harvesting. The results show that the average carbon intensity was estimated to be 21.48 kg CO_2 eq/t of sugarcane produced. The top three sources of greenhouse gases were N_2O emissions from fields (41 %), energy use in sugarcane cultivation (29 %), and application of nitrogen fertilizers and biomass residues (13 %). Scenario parameters for 2028 also forecast a cultivated yield of 59.3 t/ha. Carbon dioxide footprint reduction is expected to be up to 15 % (18.2 kg CO_2 eq/t). Most CO_2 emissions come from agricultural practices (62 %). This is the first analysis of the carbon footprint of sugarcane farming in Bolivia. Developing technologies to increase sugarcane yields while reducing nitrogen fertilizers and diesel use in agricultural activities is becoming a priority for the country to meet environmental goals.

1. Introduction

Currently, there is a growing global interest in biofuels (Alazaiza et al., 2023) because they have the potential to satisfy the demand for energy services (Bharathiraja et al., 2017) while contributing to sustainable development, whereas fossil fuels involve rapid depletion of limited resources (Erdiwansyah et al., 2019) and an increase in greenhouse gas (GHG) emissions (Capilla et al., 2022).

GHG emissions, which have increased by 75 % since the 1970s, include carbon dioxide, methane, and nitrous oxide (Battaglia et al., 2022). In the 1990s there was an increase in carbon dioxide emissions of 1.5 ppm/y, in the 2000s approximately 1.9 ppm/y, and from 2010 to 2020 approximately 2.35 ppm/y (Lan et al., 2024). Consequently, the concentration of GHG in the atmosphere has been steadily increasing: in 2022 the NOAA (National Oceanic and Atmospheric Administration) laboratory in the United States reported an average of 420.99 ppm of carbon dioxide in the atmosphere, showing an increase of 1.8 ppm from the previous year (NOAA, 2022).

According to the World Bank report, Latin America and the Caribbean produced 8.0 % of global GHG emissions (World Bank, 2022). The Agriculture, Forestry, and Other Land Use (AFOLU) sector presents the largest amount of emissions of GHG by sector, accounting for approximately 60 %, followed by the transport sector, with approximately 15 % of the total of 3690 thousand tons of CO_2 eq reported in the year 2021 (Guizzardi et al., 2023) showing an increasing trend since the year 2000 (Lamb et al., 2021). In parallel, the largest GHG-emitting sub-sector in the transport sector corresponds to road transport. This happens because vehicles such as buses, light, medium, and heavy trucks consume petroleum derivatives and, although they constitute a smaller share of road transport vehicles, around 60 % of the CO_2 emissions generated by the sector come from this group (Tanco et al., 2023).

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In the last ten years, the bioeconomy has flourished in several Latin American countries through the elaboration of different political measures (Rodriguez et al., 2019) because these countries are facing the problems caused by emissions related to burning fossil fuels in the transport sector. Significantly, several countries have been adopting measures related to the use and production of ethanol.

In Argentina, the government launched a new public policy on mandatory biofuel blending (new Biofuels Law 27,640, of July 2021), establishing new criteria for the blending as 12 % ethanol in gasoline (E12) and 5 % biodiesel in diesel (B5). Ethanol production in Argentina exceeded one billion liters in 2019 (USDA, 2021). In Colombia, based on Law 693 of 2001 for ethanol and Law 939 of 2004 for biodiesel, the government established the highest blending mandate: 10 % for ethanol and 12 % for biodiesel (Canabarro et al., 2023). In 2017, Law no. 13,576 published by the Brazilian Ministry of Mines and Energy established a new policy in Brazil, known as RenovaBio, whose objectives include promoting the expansion of the production and use of biofuels in the national energy mix (Ribeiro and da Cunha, 2022).

While governments often clearly understand GHG emissions within their geographic boundaries, quantifying their emissions upstream and downstream of the value chain is challenging (Hertwich and Wood, 2018). Likewise, there is a potential GHG emissions effect associated with the AFOLU sector due to the production of biofuels in the agricultural phase (Calvin et al., 2016), which means that the potential benefits of using biofuels in the transport sector in Latin America may be affected by potential emissions from the AFOLU sector (Picoli and Machado, 2021).

The Bolivian government ratified the Paris Agreement in 2016 and presented its Nationally Determined Contributions (NDC) to the United Nations Framework Convention on Climate Change (UNFCCC) (Fernandez Vazquez et al., 2022). In 2018, it started producing ethanol from sugarcane mixed with gasoline to reduce GHG emissions and the cost of importing fuel (USDA, 2018). Also, in 2021, the increment of the blending mandate for ethanol in gasoline was approved from 10 % to 12 % (Jeanete, 2023).

An agreement was signed between the government and the private sector (sugarcane producers) in which the aim was to produce 80 million liters of anhydrous ethanol using sugarcane as raw material, with the expectation of reaching 380 million liters in 2025 starting with a production of 10 % and gradually increasing to 25 % until 2025, estimating to expand the sugarcane cultivation area up to 305 thousand hectares, almost doubling the 172.6 thousand hectares harvested in 2019 (Peña Balderramana et al., 2020).

Based on these aspects, the focus of this study was to evaluate Bolivia's GHG emissions potential within the scope of the policies for ethanol production in the agricultural phase that the country has implemented until 2028. Based on information obtained through personal reports from sugarcane farmers and government reports, a carbon intensity inventory was compiled to estimate the carbon intensity of sugarcane produced in Bolivia.

2. Materials and Methods

2.1 Study area and data collection

Greenhouse gas estimation from sugarcane cultivation includes four distinct phases: (1) definition of objective and scope (including functional unit and system boundaries); (2) life cycle inventory (LCI) analysis; (3) life cycle impact assessment (LCIA); and (4) the interpretation of the life cycle with the delimitation of the work area (Romano et al., 2021).

The main sugarcane plantations are found in the Bolivian department of Santa Cruz (94.3 % of the sugarcane produced in Bolivia) (INE, 2022). The selected study area corresponds to the municipalities Fernández Alonso, Mineros, and Montero, all located in the Obispo Santistevan province and the municipality of Warnes located in the Warnes province (MDPyEP, 2021), representing 69 % of the sugarcane planted area in the department of Santa Cruz (MDPyEP, 2023).

Institutions such as the Bolivian Chamber of Commerce, the National Statistics Institute, and the Bolivian Alcohol Producers Association report data about sugarcane planted the region, and the expected ethanol production capacity is equal to 260 million liters per year. To obtain data at the farm level to estimate the CI (Carbon Index) of sugarcane, a collection of historical data was prepared on the key parameters essential for carrying out an LCA of greenhouse gas emissions using different sources of information such as: direct contact with farmers, government reports published through the official page of the Ministry of Productive Development and Plural Economy, and historical data recorded in the National Statistics Institute (INE) database.

The main information collected was farm size, sugarcane yield, the use of agricultural energy, the types of main sources of energy supply and consumption, the types of fertilizers, the use of other chemical products, such as insecticides and herbicides in the 2022-2023 crop year.

In this way, the aim is to have a representative sample for input data for the life cycle inventory.

2.2 Feedstock carbon intensity calculator tool and the GREET model

The Argonne National Laboratory, sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), has developed a full life cycle model called GREET (Greenhouse Gases, Regulated Emissions and Energy Use in Technologies). It allows researchers and analysts to evaluate various vehicle and fuel combinations based on the complete fuel cycle/vehicle cycle.

The U.S. Department of Energy's Advanced Research Projects Agency for Energy (ARPAE) has supported the Systems Assessment Center, an area within Argonne's Energy Systems Division, to examine CI variations of different agricultural practices and provide results of evidence-based research, during the agricultural production of crops involved in the production of biofuels. In this context, the Feedstock Carbon Intensity Calculator (FD-CIC) tool was designed, the first version of which took into account user-specific input data at the level of the farm for corn production, along with the life cycle inventory (LCI) (Liu et al., 2021)

Key parameters that affect the CI of biofuel feedstock include sugarcane yield (related to sugarcane productivity, the total volume of ethanol produced per coupled land area, and the sugarcane conversion rate – from sugar to ethanol, fertilizer/chemical application rates, and agronomic practices.

The global warming potential of each parameter in the study is calculated using Eq(1). The GHG emissions potential of the crop can be calculated as follows using Eq(2)

$$GWP_i = QP_i . EF_i \tag{1}$$

$$GWP_{crop} = \sum_{i=1}^{n} QP_i * EF_i \tag{2}$$

where GWP_i denotes the Global Warming Potential of parameter i (g GHG/t of sugarcane produced), the term QP_i is the quantity of parameter i used per ton of sugarcane produced, the EF_i refers to the emission factor of parameter i, included in the GREET model database. Also, n is the number of parameters considered in the case.

2.3 Parametric sensitivity analysis and Monte Carlo simulations

A parametric sensitivity study corresponds to the study between the variations of a result and the sources of variation in the input data within an established mathematical model. This variation can be represented as Eq(3):

$$\frac{dy}{dx} = f(x, y, \varphi) \tag{3}$$

The variable y denotes the dependent variable, x is the independent variable, and f denotes a continuous and differentiable function in all its arguments, so that for $y_0 = y(0)$, it has a unique, differentiable, and continuous solution in x and φ represented by: $y_0 = y\,(x, \varphi)$.

The uncertainty of one or more parameters cannot be extrapolated directly to the potential variation in the intensity of GHG emissions (Jonker et al., 2019). Therefore, a Monte Carlo simulation was carried out to quantify the confidence intervals of GHG emission intensity. A greater variety of scenarios find more appeal in the Monte Carlo simulation approach due to its support for various probability distribution functions, parameter correlations, complex models, and significant uncertainties. Each variable has a specific probability distribution used in Monte Carlo analysis. Likewise, the distribution of each parameter is based on available data. In the Monte Carlo simulation, all main input parameters are varied simultaneously according to their probability distribution. Consequently, the simulation results are probability distributions for the GHG emission intensity.

The propagation of probability distributions is decisive to carry out a correct assessment of the measurement uncertainty of an output quantity Y, which can be understood as a known function f of several input quantities X_i. By defining and fitting probability density functions g_{X_i} for each of the input quantities X_i, the probability density function g_X of the output quantity Y can be propagated by solving Eq(4):

$$g_Y(\eta) = \int_{-\infty}^{\infty} \dots \int_{-\infty}^{\infty} g_{X_i}(\xi_i)\delta\big(\eta - f(\xi_i)\big)d\xi_N \dots d\xi_1 \tag{4}$$

The function δ denotes the Dirac delta function, while η and ξ_i correspond to the variables that describe the possible values of the output quantity Y and the random variables X_i, respectively (Possolo and Iyer, 2017).

The Monte Carlo simulation method provides a general numerical approximation to obtain a representation of the probability density function $g_Y(\eta)$. To do this, a large number of repeated random samples (simulation results) of the probability density functions $g_{X_i}(\xi_i)$ are estimated and the results of the known function f are calculated repeatedly (Molina-Castro, 2022).

3. Results and Discussions

The potential for greenhouse gas emissions from sugarcane cultivation is 21.48 kg CO_2 eq/t of sugarcane produced. The sensitivity analysis results are presented in Figure 1, where the variation for the most important parameters in the agricultural stage were 20, 35 and 65%, thus evaluating the variation in crop emissions.

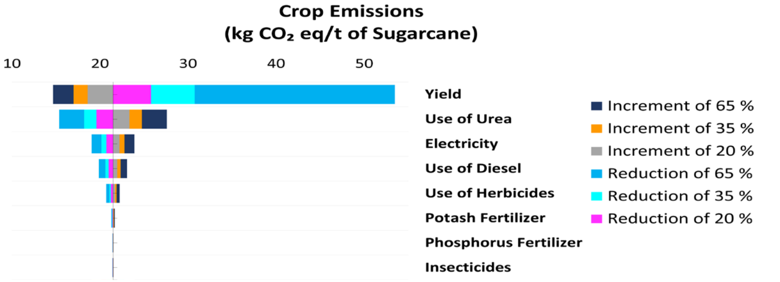

Figure 1: Tornado chart for GHG emissions from sugarcane cultivation

The variables that had the greatest impact on GHG emissions in the agricultural stage were the yield from sugarcane cultivation, the use of urea (the main chemical fertilizer used in Bolivia), and the use of electrical energy in planting and harvesting tasks. The results are consistent with the study carried out by Arcentales-Bastidas et al. (2022) in Ecuador, in which it was determined that sugarcane yield is the variable that has the greatest impact on the GWP of sugarcane cultivation. Likewise, the study by Silva et al. (2020), developed in Brazil, states that the use of nitrogen fertilizers is among the three agricultural variables that have the greatest environmental impact on GHG emissions from sugarcane crop. An increase in the yield of sugarcane cultivation by 35 % implies a potential reduction in the crop's emissions of up to 17.01 kg CO_2 eq/t of sugarcane and an increase of 65 % has the potential to reach a value of 15.00 kg CO_2 eq/t of sugarcane. Likewise, a reduction in urea application of 20 %, 35 %, and 65 % implies a greenhouse gas potential of 19.60, 18.19, and 15.37 kg CO_2 eq/t of sugarcane, respectively.
For the Monte Carlo simulation, forecasts were prepared for the variables that were reported most often, that is, the variables for which more information was available. Information related to crop yield and urea use is presented in Figure 2a, while information related to the use of insecticides and herbicides is presented in Figure 2b.

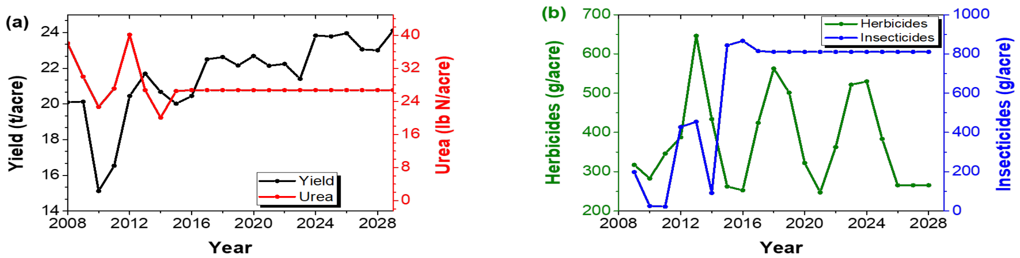

Figure 2: Forecast scenarios. (a) Crop yield and urea use; (b) Insecticides and herbicides use

Based on historical data, the probability of yield reaching a value of 24 t/acre (59.3 t/ha) over the next four years is 95 %, and a forecast urea use of 12.1 kg of nitrogen per acre of cropland was determined. Regarding the use of herbicides and insecticides, there is a forecast for the next four years of 0.38 and 0.81 kg/acre of cultivated land. Histogram (Figure 3) reported the probability distribution of greenhouse gas emissions from sugarcane.

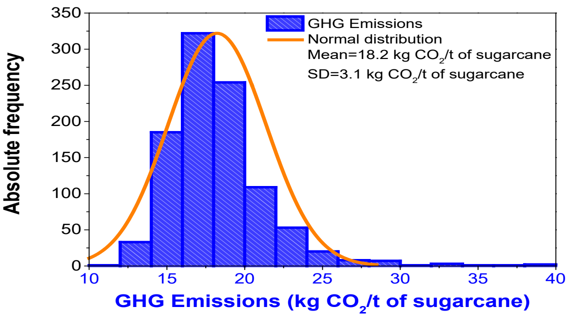

Figure 3: Probability distribution obtained through Monte Carlo simulation

The result is a normal probability distribution whose average greenhouse gas emissions based on forecasts for the next three years is 18.2 kg CO_2 eq/t of sugarcane.

4. Conclusions

Bolivia began producing ethanol for mixing with gasoline only in 2018, starting with a 10 % volumetric fraction blend intending to reach a 25 % blend in 2025. To guarantee future supply, expansion of the cultivated area is planned. However, this measure does not guarantee the sustainable development of sugarcane, as although greater ethanol production is guaranteed and consequently a lower environmental impact of the road transport subsector, the potential environmental impact of the agricultural sector is still present. The results of LCA of this study indicated that the current carbon intensity of sugarcane cultivation in Bolivia is 21.48 kg CO_2 eq/t of sugarcane, with potential to decrease in the next years.

In the short term, the country's government is expected to consider the importance of crop yield and implement sustainable agricultural practices that can maximize this yield. At the same time, it is important to mention that applying controlled rates of chemical fertilizers, such as urea in the case of Bolivia, is also considered an agricultural technique to maximize agricultural production.

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