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Research article

Energy Return on Investment (EROI) and Life Cycle Analysis (LCA) of biofuels in Ecuador

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ABSTRACT

In Ecuador, the net energy contribution of biofuels is unknown or unnoticed. To address this issue, we determined the Energy Return on Investment (EROI) for bioethanol and biodiesel.

The selection of raw materials relied on their productive capacity, export and import records, and historical yields. Consequently, the scope included three raw materials for ethanol (sugar cane, corn, and forest residues) and four for biodiesel (African palm, pinion, bovine fat, and swine fat).

Using a method based on the Life Cycle Analysis (LCA) of each biofuel, we assessed the entire production chain through statistical processing of primary and secondary information. Then we calculated the calorific values in the laboratory, compared energy inputs/outputs, and finally obtained the energetic returns.

EROIs for bioethanol were: 1.797 for sugarcane, 1.040 for corn, and 0.739 for wood. The results for biodiesel were: 3.052 for African palm, 2.743 for pinion, 2.187 for bovine fat, and 2.891 for swine fat. These values suggest feasibility only for sugarcane in the case of ethanol. In contrast, biodiesel has better prospects because all the feedstocks analyzed had EROIs higher than two. Nevertheless, biodiesel is not available for trading in Ecuador because energy policy has overlooked systems based on higher energy return. Future studies should consider more comprehensive variables such as climate change, land use, and water management.

1. Introduction

Globally, the use of biofuels in the transport sector increased 7% in 2018 (International Energy Agency, 2019). However, this growth was insufficient to achieve the international objectives set in the Sustainable Development Scenarios for 2030 (United Nations, 2015), since this commitment would require tripling bioethanol and biodiesel content in final blends, involving around 10% of global transport (Sawin et al., 2018). Several issues have slowed the incorporation of biofuels into worldwide transportation, for example, competition with the food sector for the use of feedstocks (Ho et al., 2014), the decrease in the calorific value due to the presence of oxygen (Oh et al., 2018), stillage handling and disposal (Silva et al., 2011), and the Energy Return on Investment (EROI) (Jessica G Lambert, Hall, Balogh, Gupta and Arnold, 2013).

The EROI is directly or indirectly linked to the achievement of well-being, energy quality, and energy sovereignty (Jessica G Lambert et al., 2013). It describes the amount of energy a source requires to deliver a unit of energy to society, and considers the energy flows involved in all stages of the production process (Hall et al., 2009). Several methods for calculating the EROI have been published that contain points of agreement, but also methodological differences. The main disagreements relate to the way energy flows (Moeller and Murphy, 2019), system boundaries, and residual energy embedded in co-products are identified and quantified (Capellán-pérez, Castro, Javier and González, 2019).

The Ecuadorean government has sought alternatives for reducing oil derivative imports to meet the local demand. These endeavors have intensified since last year, and in April 2019, the Ministry of Agriculture announced the Agrofuels Plan, which would replace 30,000 ha of rice with sugar cane to produce bioethanol (El Universo, 2019). The program would also incorporate 140 million liters of African palm oil per year to begin producing 15% v/v biodiesel (B15) (Ministry of Agriculture., 2019) (ASTM Specification D6751, 2010). Reducing imports would have a significant effect on Ecuador's economy because, since the 70s, the country has maintained a subsidy on gasoline, diesel, and liquified petroleum gas (Rivadeneira, 2019). This public expenditure is increasingly unsustainable with demand increasing at around 2.5% annually, fuel migrating to other consumer sectors, and the volatility of international derivative prices (Espinoza and Guayanlema, 2017). In this context, Ecuador has partially promoted the incorporation of biofuels into the energy supply (Consejo Nacional de Planificación, 2017) (Ministerio de Electricidad y Energía

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Renovable, 2017b) (Presidencia del Ecuador, 2012). For example, since 2012, a mixture of gasoline and anhydrous ethanol (5% v/v), has been available for trading in the local market (Castro, 2012). Concerning biodiesel, the blends B5, B10, B15, and B20 have been mentioned officially (Agencia de Regulación de Hidrocarburos, 2013), but none have a real share in the transport sector. Currently, the only energy use of vegetable oils is project "Zero Fossil Fuels in Galapagos" (Programa de las Naciones Unidas para el Desarrollo, 2016) (Ministerio de Electricidad y Energía Renovable, 2017a). This initiative generates electricity through direct combustion of oil without previous transesterification.

Ecuador produces 225 million BOE (barrels of oil equivalent) of primary energy; it exports 65%, and about 23% is retained as feedstock for refineries (Ministerio Coordinador de Sectores Estratégicos, 2016). This production is insufficient to cover domestic demand. Thus, in 2018, about 40% of the local consumption of diesel, gasoline and liquefied petroleum gas was imported (Cámara de Comercio de Quito, 2018) and from January to August 2019, these imports increased 16.8% compared to the same period of the previous year (Banco Central del Ecuador, 2018) (Planificaci et al., 2019). Consequently, the government has encouraged researchers and industrialists to design alternative fuels using economically viable and environmentally friendly feedstocks, as mentioned in the Agrofuels Plan (Banerjee et al., 2019) (Eduardo Rosero, 2011).

The share of biomass in the energy matrix is less than 3%, and it is used mainly for cooking food and generating electricity (Ministerio Coordinador de Sectores Estratégicos, 2016). In second place is the production of anhydrous ethanol for the "Gasolina Ecopaís" project (about 100 million liters) (Petroecuador, 2018). The production per inhabitant is comparable with countries of the region such as Colombia (Unidad de Planeación Minero Energética, 2018) or Uruguay (Ministerio de Industria Energía y Minería, 2017). However, comparison with world leaders such as Brazil (Energy Research Office, 2018) reveals a big gap of almost 12 to 1.

It is essential for Ecuador to evaluate the actual energy contribution of biofuels and the degree of flexibility of their net output in relation to changes in production process and technology. EROI is a proper tool to carry out this evaluation since it considers the entire production cycle from planting until it is ready for blending (Murphy and Hall, 2010). First, the study developed an extensive survey of the different raw materials with energetic potential (Instituto Nacional de Preinversión, 2014), namely agricultural and forestry crops with higher production records and yields, such as sugar cane, corn, wood, African palm (Figueroa de la Vega, 2008), and pinion (Instituto Interamericano de Cooperación para la Agricultura, 2016). For livestock, the analysis included resources such as cattle, pigs, goats, and sheep, and focused on their transesterifiable fat content. Then we determined the energy expenditure index (Murphy et al., 2011) using the Life Cycle Analysis (LCA). This method permitted us to break down existing biodiesel and bioethanol production processes (Tomi and Schneider, 2017). The analysis included the collection and statistical treatment of secondary information about industrial plants in operation in Ecuador and other countries. The third part consisted of determining the lower calorific value and an elemental analysis by applying standardized methods for quantifying energy availability. Finally, the relationship between the amount of energy produced and consumed was estimated using the EROI concept (Jessica Gail Lambert, Hall, Lambert and Balogh, 2013).

Few studies encompass the energy return of biofuels from different origins at the same time. Furthermore, we included agricultural products with few records in the literature, such as animal fat, pinion oil, and forest residues. The objective was to group the most compelling possibilities and present their energy advantages in terms of EROI. This information is essential for allocating resources to programs that have the best energetic benefits. The presence of economic externalities does not influence EROI; instead, it relies on the concept that humans use the best resources first (Hall, 2017). The research includes biofuels that are being or could be used in Ecuador, based on the characteristics of local industry. It incorporates the data treatment of the agricultural product to be analyzed, such as cultivation, consumption, import, and export, as well as the different levels of raw material allocation for biofuel production. The results permit us to see in a glance the effectiveness of policies implemented to meet energy requirements, given that sectors with more significant demands should be addressed first with higher EROI biofuels. This method is easy to replicate and allows the particularities of each country to be considered.

2. The situation of biofuels in Ecuador

2.1. A regional analysis of biofuel production

The successful implementation of a biofuel program depends on technology, economics, environmental sustainability, and public policy support (Saravanan et al., 2018). Governments of the region regulate their specifications by enacting minimum levels of ethanol or biodiesel content in blends (Vázquez et al., 2016) (see Table 1).

The prospects of biofuels depend on the behavior of international energy markets (Pro Ecuador, 2013) (Energy Information Administration, 2019). For instance, the fall in the oil prices in 2020 (USD 30 per barrel) would result in a severe decrease in the demand for biofuels, and lead to the collapse of their global price in the mid-term (Getachew Nigatu, Kim Hjort, Agapi Somwaru, 2015). Environmental standards, energy security, rural economic activation, and climate change will drive bioethanol consumption in the U.S. and the E.U., which, together with Brazil, would remain as the leading producers worldwide (Getachew Nigatu, Kim Hjort, Agapi Somwaru, 2015). Their production would increase from 76 billion liters in 2012 to about 100 billion liters by 2022. Additionally, emerging economies like China, Thailand, and India would contribute up to 10 billion liters of ethanol by 2020 (U.S. Department of Energy, 2019). Global expansion of biodiesel is expected to increase from 15 to 30 billion liters between 2012 and 2022 (Union zur Förderung von Oel - und Proteinpflanzen e.V., 2017). Again, the E.U., U.S., and Brazil would dominate the market with good participation by Argentina in South America. This production will utilize 15% of the world's vegetable oil (Pro Ecuador, 2013).

2.2. Local analysis of biofuel production

Ecuador began producing biodiesel from African palm in 2005, and up to 2012, all production was for export. In 2013, when national production reached 140 million liters, the government enacted Executive Decree 1303 establishing B5 blending for biodiesel. This proportion was supposed to increase gradually to B15, which would mean achieving a production of 480 million liters of biodiesel per year. For anhydrous ethanol, production started in 2012 with Ecopaís gasoline, which was to contain up to 10% anhydrous bioethanol. The National Fuel Trade Agency (ARCH) states that only Ecopaís gasoline (5% v/v) is available in the current market, and biodiesel will have to wait for distribution and marketing policies (Hernan, 2018). The use of vegetable oil is limited to pilot projects such as Zero Fossil Fuels for Galapagos and the Juan José Castelló Zambrano Foundation, in cooperation with Termopichincha; they have been burning pinion oil without transesterification to generate electricity since 2016.

Agricultural zoning published by the Ministry of Agriculture (MAG) identified the provinces with highest potential for the production of sugar cane (Guayas 74%, Loja 12%, Cañar 7%, Imbabura 4% Los Ríos 1% and Carchi <1%) and African palm (Esmeraldas 58%, Los Ríos 11%, Sucumbíos 9%, Pichincha 7%, Santo Domingo de los Tsáchilas 5%, Orellana 4%, and Guayas 2%) (Instituto Nacional de Preinversión, 2014). This information is essential for evaluating the energy required to transport biofuels to blending centers (enclosed in thick lines on the maps).

Figure 1 shows the geographical distribution of the energy potential of sugar cane on the left (15 740 TJ) and African palm on the right (87 830 TJ) (Instituto Ecuatoriano de Estadística y Censos, 2017). This record includes fermentation, transesterification, direct combustion,

Table 1. Specifications of biofuels in the region.

	Content in the blend (%)	
	Biodiesel	Bioethanol
Argentina	10	12
Bolivia	20	-
Brazil	7	18 to 27.5
Colombia	8 to 10	8
Ecuador	Up to 20	Up to 20
Peru	5	7.8

Source: Data Adapted from Management of Policies and Economic Analysis 2016

gasification, and pyrolysis. Although the potentials do not include energy return, the advantage of African palm is clear in terms of available energy.

3. Methodology

3.1. Energy Return on Investment (EROI)

The EROI calculated in this research includes the energy associated with refining and transporting fuel to the country's main point of distribution where blending would take place. The ratio of this amount of energy to the energy obtained when burning the fuel is called the Energy Return on Investment – Point of use ($EROI_{pou}$) (J. Lambert, Hall, Balogh, Poisson and Gupta, 2012).

$$EROI\_pou = (Energy\_returned\_to\_society) / (Energy\_used\_to\_get\_and\_deliver\_that\_energy) \tag{1}$$

Eq. (1) described by (Hall et al., 2009).

The EROI is a useful decision-making tool before exploiting an energy resource or when defining public policy. For example, a value of 10 or 10:1 means that society would benefit from this energy resource by 90%, and the remaining 10% is necessary to obtain that energy. This proportion varies considerably depending on the source. For example, gas and oil can have an EROI of 20:1, but in the case of tar sands, the EROI decreases to 4:1. The value for coal is usually higher and can be up to 46:1. Among the most compelling renewable energies, the EROI is 84:1 for hydroelectric generation and 18:1 for wind power (J. Lambert et al., 2012). For the specific case of biofuels, the values are less encouraging; for example, ethanol from corn has EROIs that range from 1.2 to 1.6 in U.S. distilleries (Murphy and Hall, 2010).

The source is not the only factor that determines the EROI; other inputs such as technological improvements or depletion can play crucial roles. Gagnon et al. addressed this topic for oil and gas production worldwide. The EROI increased from 26:1 in 1992 to about 35:1 in 1999, and then it decreased again to 18:1 in 2006 (Gagnon et al., 2009). Here it is clear that during the first period from 1992 to 1999, the energy return increased thanks to technological advances and extraction methods; however, during the second period from 1999 to 2006, depletion of the sources exceeded the benefits achieved through technological advances. Charles Hall (the originator of the concept of EROI) states that to keep our civilization working in the way we know it, energy systems should have EROIs higher than 5 (Hall et al., 2009).

3.2. Factors affecting the calculation of the EROI

The EROI can vary depending on the system components; for example, boundaries and outputs/inputs assumed in the energy balance, and local particularities such as production methods, types of raw materials, and energy consumed for environmental remediation (see Figure 2).

LCA starts as a horizontal analysis tool and examines the inputs and outputs of every component of the process. Then it carries out a vertical analysis of the activities of each stage (Petraru and Gavrilescu, 2010), while seeking not to include irreversibilities that are not useful to society (Arvesen and Hertwich, 2015). In general terms, this tool includes the

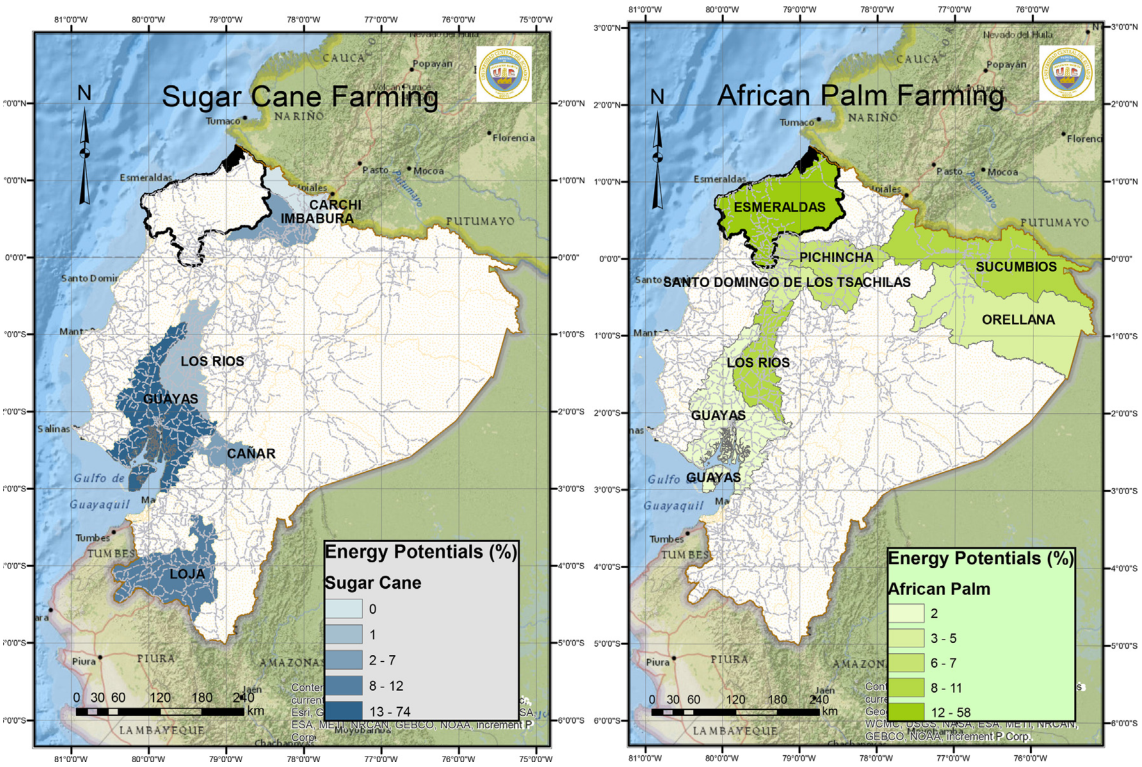

Figure 1. Bioenergy potential for sugar cane and African palm.

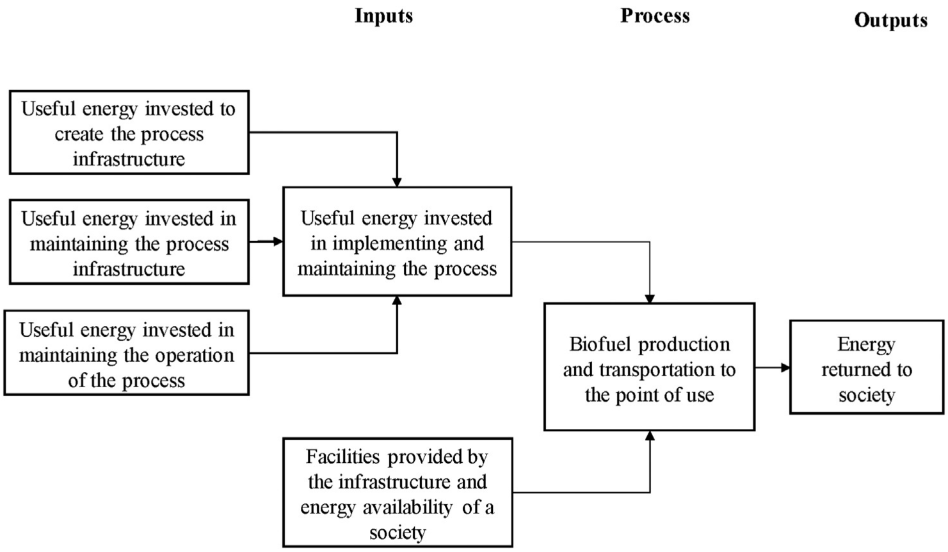

Figure 2. Description of the drivers involved in EROI calculations.

definition of objectives, scope, inventory analysis, impact assessment, and interpretation of results.

In Ecuador, ethanol comes from sugar cane only; therefore, energy consumption data are from actual industrial plants. In contrast, there is no industrial production of biofuels based on corn, wood, fat, or African palm. Hence, statistical tools and case studies are needed to determine the relationship between the energy consumption "dependent variable" and the raw material "independent variable." For biofuels production, this information allows the construction of four scenarios with different levels of corn, wood, fat, and African palm designated. This approach is based on the concept of economy of scale, where the unitary production cost decreases as the scale of operation increases.

3.3. Analysis and selection of methodology

All investigations that seek to determine the EROI of any resource use one of the following three techniques: process analysis, economic input-output, or a hybrid of both (Murphy et al., 2011).

Looking for the implications of energy return in society (Jessica Gail Lambert et al., 2013), reviewed the EROI of different sources. The most relevant references are presented below with a description of the technique used in each case (see Table 2).

Table 2. Techniques used in published EROIs adapted and extended from (Murphy et al., 2011) and (Jessica Gail Lambert et al., 2013).

Source	Reference	Technique
Ethanol and biodiesel production	(Pimentel and Patzek, 2005)	Process analysis
Oil and gas discovery and production	(Guilford, Hall, O'Connor and Cleveland, 2011)	Process analysis
Oil and gas production	(Guilford et al., 2011)	Hybrid
Oil gas and tar sand production	(Poisson and Hall, 2013)	Process analysis
Oil and gas production	(Hu et al., 2013)	Economic input-output
Ethanol production	(Diotto and Irmak, 2016)	Process analysis
Ethanol and biogas	(Arodudu et al., 2017)	Process analysis
Electricity supply	(Palmer, 2018)	Hybrid

The technique employed in each case defines the methodology and the instrument used to identify and account for energy flows. It consists of two dimensions. The first describes the boundaries of the production chain from cultivation to distribution; these are the energy outputs. The second sorts by levels and indicates the type of energy and materials directly or indirectly associated with the process. In this case, we chose level 2, which includes the energy inputs under investigation and the inputs from the other energy sectors (Murphy et al., 2011). This ensemble of dimensions results in a technique based on process analysis. The LCA is the instrument that identifies the processes within the boundaries defined in dimension one, as well as the energy flows of dimension two. The aim is to define a roadmap for selecting the proper energy balance and the type of data to be collected.

3.4. Construction of scenarios

The scenarios vary the proportions of feedstock to estimate energy consumption through linear regression models. The variance analysis of the models and the T-test for the slopes show a statistically significant relationship between the amount of raw material destined for biofuel and energy consumption, since the p-value of each test is less than the level of significance chosen ($\alpha = 0.05$). Moreover, this relationship demonstrates a high correlation between the variables according to the values of R (see Tables 3, 4; Figure 3).

3.5. Analysis of scenarios

The selection criteria rely on the scenario that results in less energy consumption during the feedstock's industrial stage. The following are the best scenarios for each case. Corn. - S4 (50%) with energy consumption in the industrial stage equal to 13.85 MJ/kg bioethanol, which is higher than industrial plants in Argentina 11.91 MJ/kg, U.S. 11.80 MJ/kg, and Chile 12.29 MJ/kg. Wood. - S4 with energy consumption of 29.880 MJ/kg of bioethanol, a level comparable to other industrial plants, 30.370 MJ/kg in the United Kingdom, 32.921 MJ/kg in Canada, and 46.766 MJ/kg in Brazil. African Palm. – S4 (5.694 MJ/kg biodiesel), which represents 48.59% of total energy consumption. It is within the range of preliminary studies 3.87–6.58 MJ/kg biodiesel. Animal Fat. - S4 (9.045 MJ/kg), which represents 51.54% of total energy consumption; this is slightly higher than the values presented in preliminary studies (5.548–8.165 MJ/kg). Pinion. - S4 (8.259 MJ/kg biodiesel), which represents 64.81% of total energy consumption; this is higher than values presented in Peru 6.820 MJ/kg, Argentina 6.842 MJ/kg, and India 6.442 MJ/kg.

Table 3. Statistical criteria of scenarios constructed.

Statistical criteria	Corn	Wood	African palm	Fat	Pinion
Slope of the model	10981.2	9186.1	88976.2	0.2064	0.0150
Value-p significance of the slope (t test)	0.0188	0.0058	0.0022	0.0087	0.0168
Value-p significance of the model (ANOVA)	0.0188	0.0058	0.0022	0.0087	0.0168
Correlation coefficient (R)	0.9812	0.9942	0.9978	0.9913	0.9832

Table 4. Assignation levels of feedstock.

	Assignation of national production (%)			
Feedstock	S1	S2	S3	S4
Corn	10	20	30	50
Wood[1]	Imbabura.	Imbabura, and Pichincha.	Imbabura, Pichincha, and Cotopaxi.	Imbabura, Pichincha, Cotopaxi, and Los Ríos
African Palm	2	5	10	20
Animal Fat	2	5	10	20
Pinion	20	30	40	50

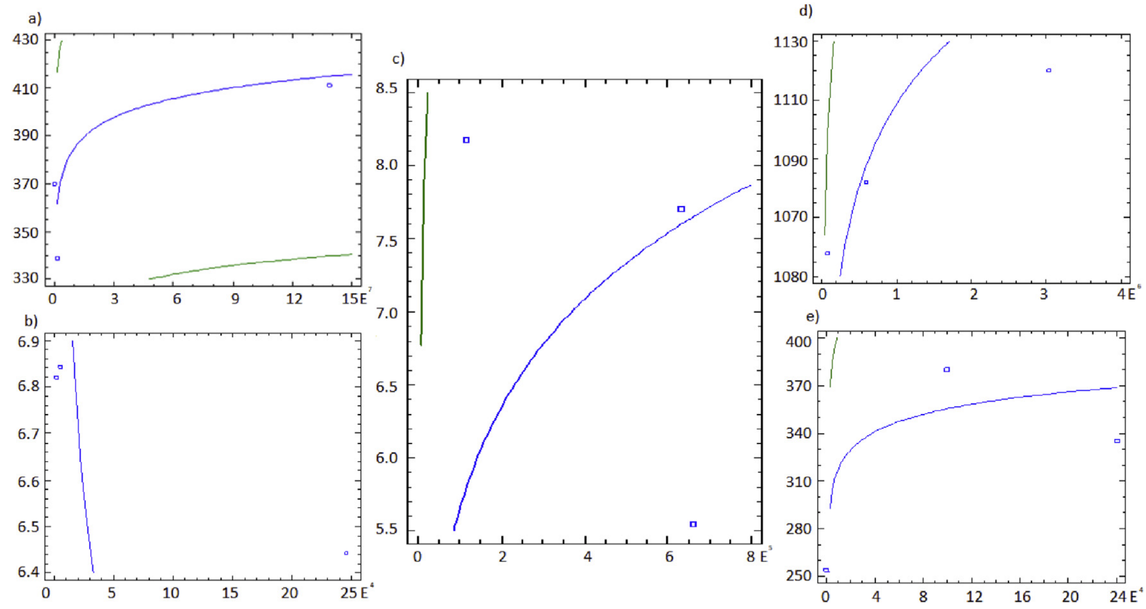

Figure 3. Adjusted models for yields (Y) in liters of biofuel, a function of feedstock (F) in tons of raw material a) corn $Y = \sqrt{(9186.16\ \ln F)}$ b) pinion $Y = 1/(0.015013\ \ln F)$ c) fat $Y = (0.206369\ \ln F)\hat{2}$ d) African palm $Y = \sqrt{(88976.2\ \ln F)}$ e) wood $Y = \sqrt{(10981.2\ \ln F)}$. The statistical analysis was carried out in Statgraphics® and the results are summarized in Table 4.

The production of biofuels generally involves the generation of some co-products; for example, glycerin in biodiesel, which accounts for approximately 10% of energy consumption. Likewise, bioethanol from corn has multiple co-products that include oils and meal for animal feed; their exclusion or incorporation into the analysis produces essential changes in the final values of the EROI. Hall et al. (2011) addressed this issue when comparing the EROI of corn alcohol, previously obtained by (Kim and Dale, 2005) and (Pimentel and Patzek, 2005), as 1.73: 1 and 0.82: 1, respectively.

Approximately 50% of this difference is due to the treatment and use of the co-products generated in the industrial process. This work excluded the subsequent treatment of co-products because of uncertainty about the allocation of the weighting factors of their energy consumption and their final use (Hall et al., 2011). Hence, the scenarios developed in this work are conservative in this sense. Similarly, we excluded the energy required for environmental remediations because it could change according to the specific obligations in each zone. Finally, Esmeraldas Refinery was used as the final destination of biofuels, since this is where the mixing of Ecopaís B5 gasoline take place. Considering these methodological aspects, the calculated EROI is very close to the EROI at the point of use, with less than 5% difference (Hall et al., 2009) (2% in our cases).

4. Calculations

We determined the energetic availability from the net amount of heat produced by fuel combustion under controlled conditions (Cengel, Yunus. Boles, 2014). Local producers and research centers provided the samples. They are listed below with the respective selection criteria (see Table 5).

Finally, we obtained the Net Calorific Value (NCV) from specialized tests, such as ASTM D240-02 and (Sader and Oliveira, 2002), for gross calorific value and elemental analysis, respectively.

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[1] For wood, the assignation relies on the total forest residues available in the different provinces.

Table 5. Criteria for the selection of biofuels producers.

Biofuel sample	Supplier	Selection criterion
Bioethanol from sugar cane	Soderal S.A.	It was selected based on industrial importance, as Soderal S.A. is one of the three companies authorized to market ethanol with Petroecuador (public hydrocarbon trading company). Its product complies with the local technical standard NTE INEN 935 and its sugar mill accounts for about 31% of national production (E.P. Petroecuador, 2019).
Biodiesel from African palm	La Fabril	Commercially, oils and fats are one of the most concentrated sectors in Ecuador according to the Center for Economic and Social Rights. La Fabril is one of eight companies that account for 83% of the national market. Since 2012, it has exported oil for biodiesel using the following method, ASTM D 6751/B100 (blends with diesel) (Lasso, 2018).
Biodiesel from animal fat	Local Producer	There is no industrialized refining of fat to biodiesel yet. Therefore, the Department of Petroleum, Environment, and Contamination (DPEC) provided a sample that complies with technical regulations in terms of calorific value. The producer is part of the DPEC customer portfolio.
Biodiesel from pinion	INER	Pinion oil, as an energy resource, is a pilot program of the Ministry of Energy and Non-Renewable Natural Resources, and INER is the implementing branch of the project (Instituto Interamericano de Cooperación para la Agricultura, 2016).

$$Q\_net = Q\_gross - 0.2122H \tag{2}$$

Where

Q_net = Net calorific value [MJ/kg]
Q_gross = Gross calorific value
H = mass percentage of hydrogen

Energy consumption involves the entire production chain, including the stages of cultivation, distribution, chemical transformation, and delivery to blending facilities. Figures 4 and 5 show the extraction of biofuels from agricultural commodities and animal fat, respectively.

The following is a model for calculating the EROI at the point of use for sugar cane in scenario 1. Other raw materials follow the same procedure.

$$EROI_i = Qnet_i / Econ_i$$

$$Ec_i = E_{farming} + E_{transportatioin} + E_{industrial} + E_{distribution} \tag{3}$$

Where:

$\mathrm{EROI_i}$ = Energy Return on Investment of feedstock i.
$\mathrm{Econ_i}$ = energy consumed by farming, transportation, industrial, and distribution stages [M.J./kg].

$$EROI_{sugarcane} = 27.700 / (8.365 + 1.106 + 5.215 + 0.739)$$

$$EROI_{sugarcane} = 1.796$$

The desegregation of formula (3) shows the decrease in EROI through the production chain. This information is also shown as a percentage, taking the cultivation stage as a reference.

$$EROI_{farming} = 27.7 / 8.365$$

$$EROI_{farming} = 3.311$$

The $\mathrm{EROI_{farming}}$ represents the energy return of sugar cane, considering cultivation only. After adding the other stages, the EROI becomes 2.925, 1.886, and 1.796 for transportation, transformation, and distribution (see Figure 6).

The $\mathrm{EROI_{farming}}$ begins at 3.311 and decreases by 11.68%, 43.04%, and 45.77% by the end of its production chain. That is, 3.311 x (100–45.77)% = 1.796. This detail allows the analysis of consumption by subprocess. For example, the EROI of forest residues decreases by 80.60% by the final stage. As a result, we obtain an EROI at the point of use that is less than one.[2]

The NCV of sugar cane, African palm, fat, and pinion was obtained experimentally, and NCV of corn and wood was theoretical. The following eight figures compare the results of the energy consumed per stage and the available NCV, to observe net benefits.

5. Results and discussion

The results confirm that energy consumption is strongly influenced by both the raw material and the industrial stage. In general terms, biodiesel has an advantage over ethanol (see Table 6).

The calculation of the EROI has been adjusted not only for the agricultural and industrial reality of Ecuador, such as ethanol from sugarcane, but also for raw materials, whose production is part of national development plans and public policies for future projects such as biodiesel. Therefore, we propose substitutive goods to generate more inputs that will allow the prediction of the net energy impact of introducing biofuels from different origins under current production conditions. Besides EROI, other socioeconomic considerations can arise, such as the creation of jobs and the activation of the agricultural sector, as well as reducing refined fuel imports resulting from the lack of internal production capacity.

The fossil fuel subsidy policy impacts the national government in two ways. On one hand, subsidized fuel increases consumption due to its low price, and the country has to allocate around USD 4 billion per year (4% of GDP) to meet the demand. On the other hand, since it does not have refining capacity to cover the domestic market, the government has to import derivatives at fluctuating prices, placing the local dollarized economy at risk year after year.

The issue gained importance in the country after October 2019, because the Ecuadorean government attempted to eliminate gasoline and diesel subsidies. The measure provoked intense social protests from several sectors, such as transport, agriculture, and industry. Finally, in the face of excessive pressure, it had to withdraw the decision. Therefore, all options that are considered should adopt an integrated analysis that includes technical, economic, and social aspects. The EROI could provide vital information to address this issue from a more insightful standpoint.

Development is strongly related to the EROI on which societies base their economies. In Ecuador, the production of primary energy from fossil fuels is close to 94%, and biofuels constitute less than 1%. However, increasing this share is a subject of constant debate and pressure from various sectors. This is where the concept of EROI plays an influential role, since it allows real-net contributions to be compared with the apparent benefits of green energy, driven mainly by actions to mitigate climate change. In many cases, those actions ignore the fact that fossil fuels provide energy for developing renewable technology. The EROI values for Ecuador range from 0.845 to 1.796 for ethanol and 1.500 to 3.052 for biodiesel. Moreover, the results show that the greatest energy demand is for cultivation (10.1–54.2%) and industrial stages (33.8–85.0%), so we compared them with regional and world values.

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[2] The calculation for the other raw materials is available at https://uceedu-my.sharepoint.com/personal/wgchiriboga_uce_edu_ec/_layouts/15/Doc.aspx?OR = teams&action = edit&sourcedoc = {F2E8D0E8-256D-493D-B526-F96AB5D2759C}.

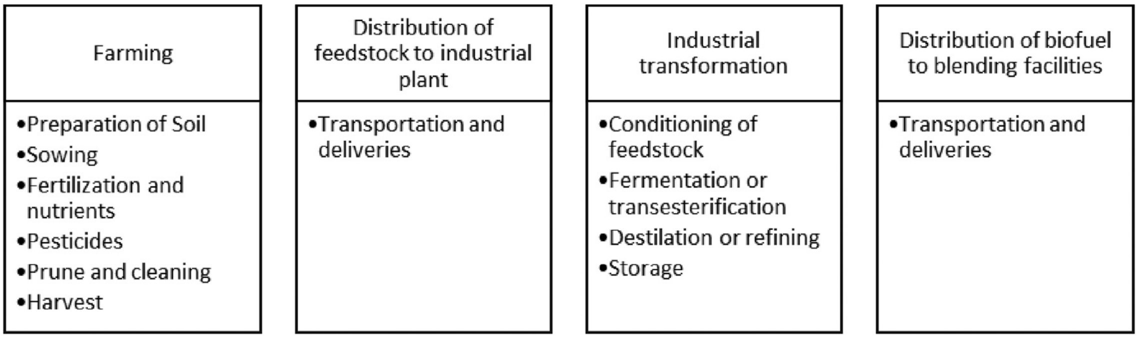

Figure 4. Stages included in the LCA for plant raw materials.

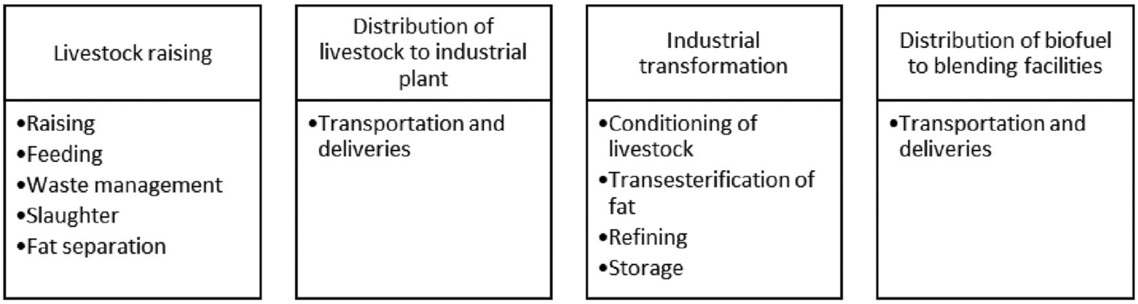

Figure 5. Stages included in the LCA for animal raw materials

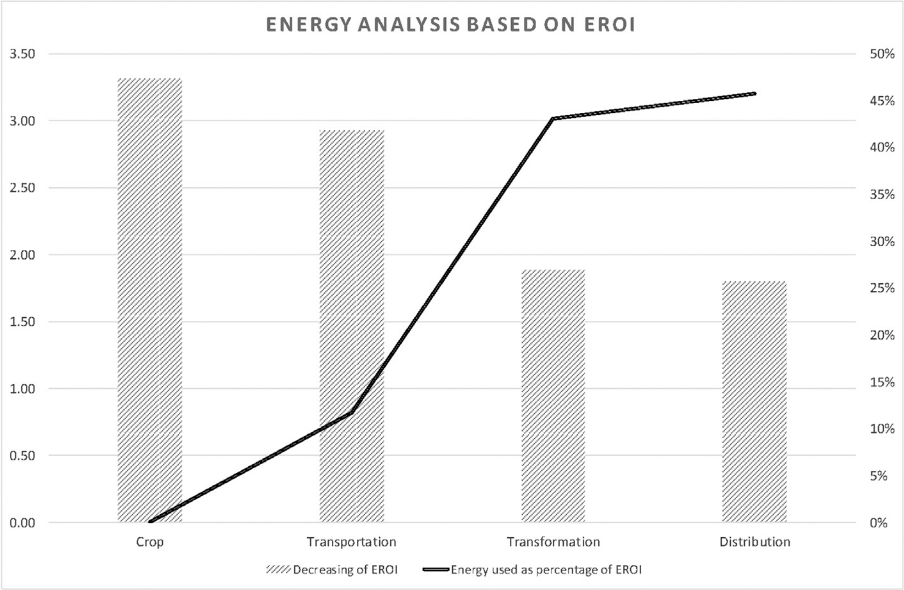

Figure 6. Decrease in the EROI due to the use of the energy necessary per stage – sugar cane.

Table 6. EROI for each scenario and raw material.

Scenario	Sugar Cane	Corn	Wood	African Palm	Pinion	Bovine	Porcine
S1	1.796	0.944	0.687	2.604	2.443	1.500	2.100
S2	1.796	0.986	0.748	2.787	2.576	1.769	2.415
S3	1.796	1.010	0.794	2.921	2.670	1.977	2.653
S4	1.796	1.040	0.845	3.052	2.743	2.187	2.891

Energy consumption for growing sugar cane is 8.365 MJ/kg, which on the average is 43.2% more energy than Brazil, but 31.9% less than the U.S. The situation is different for corn, which in Ecuador requires 11.083 MJ/kg, compared to 2.923; 6.863; and 9.053 MJ/kg in the U.S., Chile, and Argentina, respectively. For African palm, energy consumption is 5.52 MJ/kg, 89.7% higher than Indonesia and 62.2% higher than

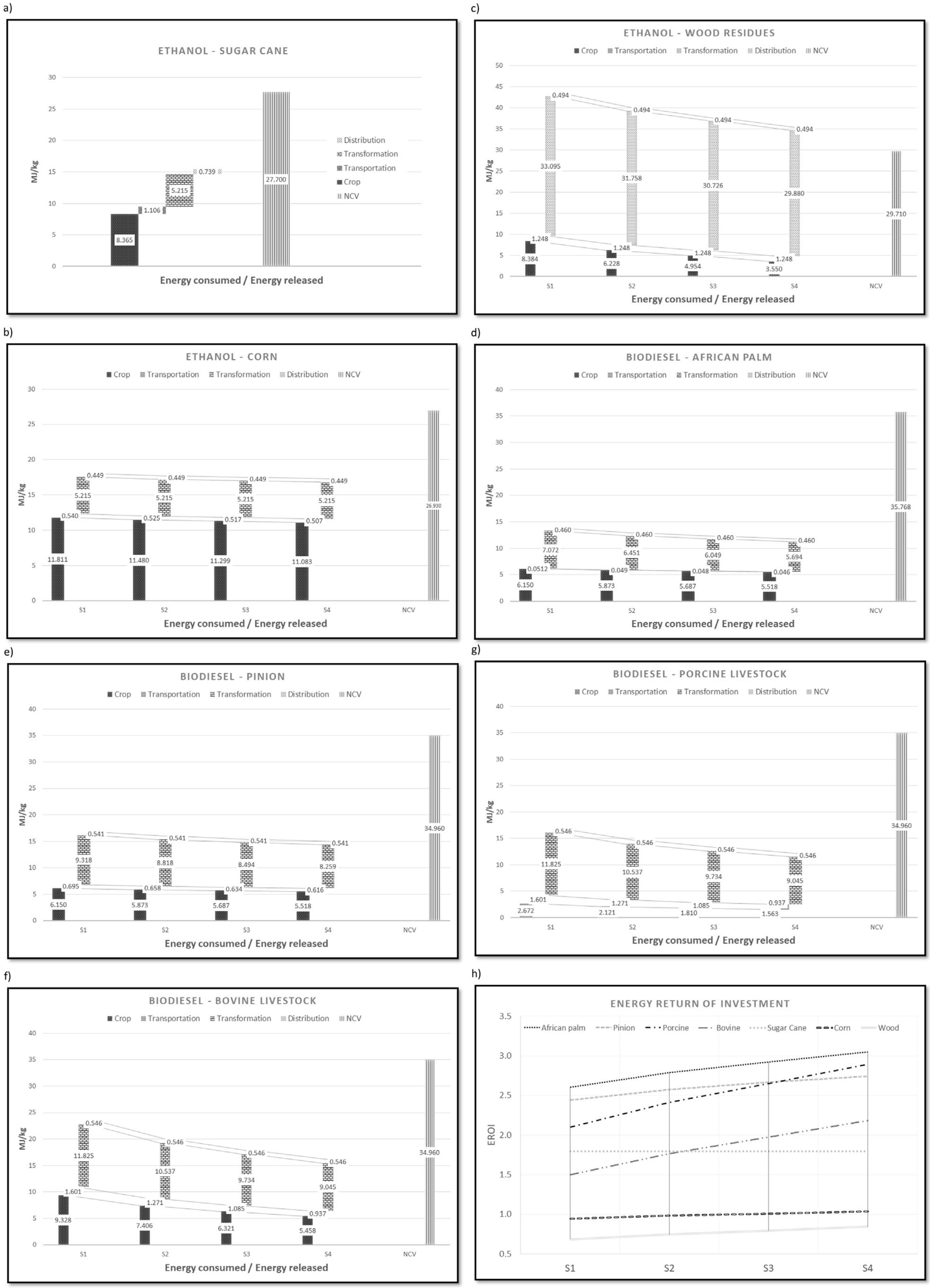

Figure 7. From a to g, breakdown of the energy consumed to produce biofuel (left), and the total energy released by combustion (right) according to the feedstock and assumed scenarios. h is a summary of the EROIpou for all the feedstocks considered and sorted by scenarios. The advantage of biodiesel is evident.

Colombia. For livestock, Ecuador consumes about 26% more energy than Mexico and Brazil, and up to 47.7% more than the U.S. Energy consumption in pig raising is significantly lower due to space management and the type of feeding, so the energy demand comes from the transesterification of fat. This investigation reports the current situation of energy management for both alcohol fermentation and dehydration and the transesterification of fat. We also considered the pretreatment and refining stages of each raw material.

In Ecuador, the incorporation of biofuels into the energy matrix has two main objectives. On one hand, it seeks to reduce the environmental impact of greenhouse gas emissions by using biomass, whose carbon comes from photosynthesis. On the other hand, it seeks to displace imports of petroleum-derived fuels, mainly gasoline and diesel, while encouraging national agricultural production. In this context, ethanol from sugar cane has the most favorable EROI, at 1.796, which leads to the following analysis. If the aim were to meet nationwide demand with Ecopaís, the energy market for anhydrous ethanol would be 1,300 kBOE (8,000,000 MJ). This amount of energy would require 360,000,000 L of alcohol (energy intensity = 22.2 MJ per liter) and 450 km^2 of arable land (Instituto Interamericano de Cooperación para la Agricultura., 2007). Fossil fuels could provide 57% of this energy; however, there would still be a contribution by renewables of about 3,440,000 MJ. For the other raw materials analyzed, there would not be a net energy contribution by ethanol. In the case of wood, there would be a negative energy balance since its EROI is between 0.687 and 0.845.

For biodiesel, we chose African palm to carry out a similar analysis, and the EROI calculated was 3.052. The production of B10 blends to meet nationwide demand would represent 3,500 kBOE or 21,400,000 MJ, and would involve around 665,000,000 L of biodiesel and 1,210 km2 of land (energy intensity = 32.2 MJ per liter). Pinion is worth highlighting because its EROI is 2.743, and it constitutes an excellent opportunity because it does not compete directly with the food sector. Only living fences are required to produce it, so it would therefore not jeopardize land use to a significant extent. Biodiesel from animal fat (cattle 2.187:1 and pigs 2.891:1) appears to be more feasible than ethanol, as shown in Figure 7h. The best production scenarios for both ethanol (sugar cane 1.796) and biodiesel (African palm 3.052) suggest that expending a unit of energy to produce biodiesel would return 1.256 more energetic units than bioethanol. Besides, data from the last National Energy Balance showed that the demand for diesel is greater than gasoline (34,500 kBOE and 25,000 kBOE, respectively) due to the high energy consumption characteristics of this subsector, and the ease of fuel utilization for industrial activities.

Finally, it is worthwhile analyzing how Ecuadorians use fuels for transportation. For example, individual or light cars consume 71% of the gasoline, and in the best case would transport five users at a time. And collective or heavy-duty transport utilizes the remaining 29%. In contrast, light and individual transport consumes 20% of the diesel and collective or heavy-duty transport utilizes up to 80%. So, since the biodiesel market would mean a higher energy return, better land use, and greater coverage of benefited users, it should be analyzed why, so far, Ecuadoreans still cannot trade biodiesel locally.

6. Conclusion and policy implications

The study presents an initial analysis of the energy return of the biofuels considered in national development plans for transport. The energy return rate of bioethanol is feasible only for sugarcane because it has an energy surplus of 1.796. For biodiesel, the values are favorable in all the selected scenarios, since its EROIpou was always greater than 2. The stages of cultivation and industrial transformation are the most energy-demanding; therefore, energy efficiency policies should begin by addressing these stages, so that we can achieve world productive yields like those of Brazil and the U.S.

The market for bioethanol as fuel is 94 million dollars (110 million liters). Petroecuador E.P. has awarded the administration of the project to three private companies and a 4% share to small farmers. This gasoline is available in 10 of the 24 provinces of the country. In 2019, it achieved first place in sales with 45% of the total market. The numbers are encouraging but the Energy Ministry has questioned the project since 2018, because it is cheaper to import ethanol from neighboring countries. The reasons are the lack of local production of agricultural inputs and the high cost of labor. Based on this analysis, the project seems to be maintained solely by the 3,000 direct jobs it generates. However, even if the objective is to prioritize job stability, the EROI could provide public policymakers with adequate information on each stage in order to correctly direct incentive programs.

The biofuels program was launched in April 2019, and included biodiesel as a priority. That year, the Organic Law of Energy Efficiency called for the creation of the necessary policies for promoting the marketing of biofuels at the national level. As of the writing of this document, there are no clear implementation programs or plans for biodiesel. In the context of energy efficiency and renewable energy, the public policy proposes the electrification of the transport matrix. By 2025, new units incorporated into public transport must only be electrically powered. This measure covers 6% of national diesel demand, but the actions to be taken for light and heavy units, which constitute 93%, are not clearly expressed. Here, encouraging EROI results provide an alternative in the medium term, mainly because biodiesel blends do not incur the drawbacks of electrical units, such as battery life, limited range, dispatchability, and recharging points.

The land required to meet domestic demand with Ecopaís and biodiesel (B10) shows similar energy densities, since both have yields of about 17.7 MJ per km^2. That is, the same amount of land would be committed to generating a unit of energy from sugar cane or African palm. However, this issue deserves further study that considers the water required and the net greenhouse gas emissions generated. We analyzed biofuels for use in transportation engines, which implies high-quality fuels and consequently, high energy demands during refining processes. Diversifying the matrix and allocating fuels for direct combustion should be considered, such as pinion, for direct use in power generation. Here, the EROIpou would increase from 2.743 to 8.864.

The unprecedented crisis in the oil markets due to the COVID-19 outbreak has caused severe impacts on oil-exporting economies, such as that of Ecuador. In this regard, some analysts suggest that prices will rise considerably in the medium term, which would imply a new increase in the cost of derivatives. Currently, Ecuador's social environment makes it highly unlikely that subsidies will be withdrawn. This forces the Ecuadorian government to generate guidelines focused on incorporating viable options for the diversification of the energy matrix to alleviate the fiscal deficit caused by the subsidy.

In the current situation of low global energy demand, Ecuador should use the opportunity to generate public policies aimed at defining how, when and what quantity of derivatives to acquire in the future, as well as the amount of raw materials to be dedicated to the production of biofuels. Both decisions must consider, among other things, the EROI as a technical criterion to indicate which biofuel to produce to minimize the impact on other energy resources and economic sectors.

Declarations

Author contribution statement

Gonzalo Chiriboga: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Andrés De La Rosa: Performed the experiments; Contributed reagents, materials, analysis tools or data.

Camila MolinA & Stefany Velarde: Performed the experiments.

Ghem Carvajal C.: Conceived and designed the experiments; Analyzed and interpreted the data.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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