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TESIS DOCTORAL

Sustainable second-generation bioenergy alternatives for Ecuador

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List of Acronyms

ADP	Abiotic Depletion
AEZ	Agroecological Zones
AP	Acidification
ARC	Aceite Reciclado de Cocina
BC	Black Carbon
BECCS	Bioenergy with Carbon Capture and Storage
CAF	Banco de Desarrollo de América Latina
CARICOM	Caribbean Community
CDM	Clean Development Mechanism
CE	Circular Economy
CHP	Combined Heat Power
COD	Chemical Oxygen Demand
CPO	Crude Palm Oil
DB	Dry Basis
EIA	Energy International Agency
EP	Eutrophication
EPA	Environmental Protection Agency
FAO	Food and Agriculture Organization of the United Nations
FEDEPALMA	Federación de Palmicultores de Ecuador
FLACSO	Facultad Latinoamericana de Ciencias Sociales
GDP	Gross Domestic Product
GHG	Greenhouses gases
GIS	Geographic Information Systems
GWP	Global Warming Potential
HTP	Human toxicity Potential
IIASA	Institute for Applied Systems Analysis
IIGE	Instituto de Investigación Geológico y Energético
ILUC	Indirect Land Use Change
INEC	Instituto Nacional de Estadísticas y Censos
ISO	International Standards Organization
LC	Land Competition
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LFG	Landfill Gas
LPG	Liquefied Petroleum Gas
LUC	Land Use Change
LUT	Types of Land Use
MAG	Ministry of Agriculture of Ecuador

MEER	Ministerio de Electricidad y Energía Renovable
MET	Marine Aquatic Ecotoxicity
MSE	Marine Sediment Ecotoxicity
MSW	Municipal Solid Waste
NDC	National Determined Contribution
ODP	Ozone Layer Depletion
OECD	Organization for Economic Cooperation and Development
OLADE	Latin American Energy Organization
POME	Palm Oil Mill Effluent
POP	Photochemical Oxidation
PV	Photovoltaic
RPO	Refined Palm Oil
TET	Terrestrial Ecotoxicity
UNFCCC	United Nations Framework Convention on Climate Change
USDA	United States Department of Agriculture
VS	Volatile Solids
WCO	Waste Cooking Oil
WF	Water Footprint
WVO	Waste Vegetable Oil

Abstract

Bioenergy demand is projected to grow to achieve climate change mitigation goals. Most climate change mitigation scenarios rely on the incremental use of biomass as energy feedstock. In Ecuador, even though, hydropower remains the most cost-effective energy source for the long term, limitations on its deployment and uncertainties related to future climate change impacts could compromise its ability to support the achievement of climate change targets. Nevertheless, literature is abundant when addressing the negative impacts of bioenergy production under unsustainable frameworks. Currently, the bioenergy share of electricity in Ecuador comes mainly from sugar cane by-products contributing 1.3% of the total electricity produced in the country. In this regard, it is crucial to increase the share of alternative sustainable energy sources as biomass to provide both peak and base electricity loads in future scenarios. On the other hand, energy security on islands is a challenging issue due to their isolation from energy markets and fossil fuel dependence. In the Galapagos Islands, electricity generation relies mainly on fossil fuels.

For the above mentioned, the overall objective of this study is to identify potential sustainable second-generation bioenergy resources for continental Ecuador and the Galapagos Islands using Life Cycle Assessment and agroecological zoning methodologies.

First, the Life Cycle Assessment of bioenergy in islands study, identified alternatives for firm electricity production in Galapagos Islands, evaluating the environmental performance of two alternatives: a) refined palm oil and b) locally produced clean waste cooking oil. Air emissions derived from electricity production from waste cooking oil and refined palm oil were directly measured and integrated into the life cycle inventory.

Results showed better environmental performance for the electricity derived from waste cooking oil in all the impact categories studied when compared to refined palm oil.

Second, the agroecological zoning of second-generation energy crops study identified 222,060.71 ha available to produce the dedicated bioenergy crops and a potential electricity production of 9,134 GWh/year, which is proportional to 31% of electricity produced in Ecuador by 2019.

Resumen

La demanda de bioenergía se proyecta a incrementarse para lograr los objetivos de mitigación del cambio climático. La mayoría de los escenarios de mitigación del cambio climático se basan en el uso incremental de biomasa como materia prima energética. En Ecuador, aunque la energía hidroeléctrica sigue siendo la fuente de electricidad más rentable a largo plazo, las limitaciones en su despliegue y las incertidumbres relacionadas con los impactos futuros del cambio climático podrían comprometer su capacidad para conseguir los objetivos de reducción de emisiones. Actualmente, la participación de la bioenergía en la matriz eléctrica del país proviene principalmente de los subproductos de la caña de azúcar que contribuyen con un 1.3% de la electricidad total producida en el país. Por lo expuesto, resulta crucial aumentar la participación de fuentes de energía alternativas y sostenibles como la biomasa para cubrir demandas eléctricas de pico y de base en escenarios futuros. Sin embargo, la literatura es abundante cuando se abordan los impactos negativos de la producción de bioenergía en marcos insostenibles. Por otro lado, la seguridad energética en islas es un tema desafiante debido a su aislamiento de los mercados energéticos y su dependencia de combustibles fósiles. En las islas Galápagos, la generación de electricidad se basa principalmente en combustibles fósiles.

En base a lo expuesto, el objetivo general de este estudio es identificar potenciales recursos bioenergéticos sostenibles de segunda generación para el Ecuador continental y las Islas Galápagos, utilizando metodologías de evaluación del ciclo de vida y zonificación agroecológica.

En primer lugar, el estudio de evaluación del ciclo de vida de bioenergía en las islas identificó alternativas para la producción de electricidad firme en las Galápagos, evaluando el desempeño ambiental de dos alternativas: a) aceite de palma refinado y b) aceite de cocina usado tratado y producido localmente. Las emisiones atmosféricas derivadas de la producción de electricidad a partir de aceite de cocina usado y aceite de palma refinado se midieron directamente e integraron en el inventario de ciclo de vida. Los resultados mostraron un mejor desempeño ambiental para la electricidad derivada de aceite usado de cocina en todas las categorías de impacto estudiadas en comparación con el aceite de palma refinado.

En segundo lugar, el estudio de zonificación agroecológica para cultivos energéticos de segunda generación identificó 222,060.71 ha disponibles para producir cultivos dedicados a bioenergía con una producción potencial de electricidad de 9.134 GWh/año, proporcional al 31% de la generación eléctrica del Ecuador en el año 2019.

1. Introduction

Most of the total energy use on the planet is based on fossil fuels such as oil, coal, and natural gas, accounting 87% and representing 511 PJ per year [1]. However, this situation is relatively new. In preindustrial times, biomass (wood, charcoal, grass, and plant residues) was the main fuel used; since those times, half of the world's society moved from the use of biomass-derived energy to the use of the fossil fuels [2]. Indeed, more than three billion people today use biomass as their main energy source [3]. In the world's poorest countries, up to 90% of all energy is supplied by biomass [4]. Bioenergy refers to biomass products that have been converted into liquid, solid, or gas form, depending on the raw material and the technology used, for energy generation. Biomass encompasses a broad spectrum of plant materials ranging from agricultural, forestry, and municipal wastes to crops explicitly grown to make biofuels, such as bioethanol and biodiesel [5]. Bioenergy is considered the main and most important renewable energy option at present, contributing 50 EJ to global primary energy demand [6]. Ecuador has an extensive diversity of raw materials that could be used to diversify and extend bioenergy use. Agricultural wastes from banana, palm oil, cocoa, and corn account with 16 million tons per year which could be used for producing energy. Besides, bioenergy growth in Ecuador grants several advantages such as reaching energy sovereignty, energy diversification and promoting the agro-industrial sector [7].

1.1. Socioeconomic situation of Ecuador

In 2018, Ecuador had 17,267,986 inhabitants, of which 23.2% live in poverty, urban poverty was 15.3%, and rural poverty was 40%; Extreme income poverty was 8.4%, with a higher incidence in the rural area (17.7%) [8]. Between 2010 and 2018, the real Gross

Domestic Product (GDP) showed an average growth of 3.38%. In 2018, Ecuador's nominal GDP reached 108 billion dollars[9]. In 2018 the total primary export account of the country was 21,606,000 USD. The main export products are petroleum and derivates 70%, Banana 11%, Shrimp 6,8%, Flowers 3,9%, and Cocoa 1,6% [10].

1.2. Ecuadorian Energy Sector and subsidies

Primary energy production in 2018 was 216 million BOE. Of the total produced, 87.5% corresponds to oil, 4.7% to natural gas, and 7.8% to renewable energy (hydropower, firewood, cane products, wind, photovoltaic, and biogas). Regarding energy consumption by sector in the country, transportation represents most of the demand (51%), then the industrial sector (16%), residential sector (14%), construction (10%), commerce and public sector (6%) and agricultural sector with (1%) [6].

During the past four decades, the share of these sectors has changed. Thus, transport is the fastest-growing sector rising from 33% of the matrix during the 1970s, to 52% in the 2000s. The residential sector was the largest consumer in the 70s (43% on average), decreasing to 20% in the 2000s. The industry has remained almost the same with constant participation of 16% in the 70s and 19% in the 2000s [11].

Regarding electricity production in 2018, Ecuador's matrix presents a 60.84% input from renewable energy, representing 13,638.89gigawatt-hours (GWh) [6]. Table 1 shows the shares per source.

Table 1. Electricity energy share in Ecuador

Rated power of electric generation		**MW**	**%**
Renewable	Hydro	5,047.00	62.39
	Wind	21	0.26
	Photovoltaic	27	0.33
	Biomass	144.3	1.78
	Biogas	6.5	0.08
Total renewable		**5,245.80**	**64.84**
Nonrenewable	Thermic IC	1636.5	20.23
	Thermic gas	776	9.59
	Thermic steam	431.6	5.34
Total non-renewable		**2,844.10**	**35.16**
Total installed power		**8,089.90**	**100**

Source: Energy Balance of Ecuador (2019)

In Latin America, it should be noted that the use of biomass as an energy source is low in countries with fossil fuel subsidies such as Ecuador (2,8%) and virtually nonexistent in highly fuel subsided economies like the Venezuelan [12].

In Ecuador, the prices of gasoline, diesel, liquefied petroleum gas (LPG), and electricity have been subsidized since the 1970s by up to 85%[13]. Table 2 shows this subsidy variation in the last 10 years per type of fuel.

In 2012, the country ranked fifth worldwide in energy subsidies as a percentage of GDP, surpassed by Saudi Arabia, Iraq, Venezuela, and Algeria; In 2014, it ranked third in Latin America [14]. In the last ten years, fossil fuel subsidies officially reported in Ecuador caused substantial pressure in the public budget equivalent to an average of US $ 2.3 billion per year, approximately 7% of public spending or two-thirds of the public deficit [15]. Diesel receives approximately half, gasoline about one third, and LPG one-fifth of the total fuel subsidies. In times of high oil prices, official subsidies increase due to the growing disparity between the world market price and the domestic fixed price of petroleum products mostly imported [16]. In the year 2019, the government of Ecuador decided to eliminate subsidies to gasoline and diesel through executive decree No. 833, and in the year 2020 through executive decree No. 1054, the government sets a system based on bands to determine the prices of all types of gasoline and diesel sold in the country.

Table 2. Subsidies for fossil fuels in Ecuador in the last 10 years

Subsidy in USD per fuel			
Year	**LPG**	**Gasoline**	**Diesel**
2009	0.42	1.08	0.76
2010	0.54	1.51	1.19
2011	0.81	2.32	1.99
2012	0.72	2.45	2.28
2013	0.69	2.35	1.99
2014	0.65	2.06	1.72
2015	0.32	1.01	0.81
2016	0.57	0.38	0.62
2017	0.47	0.30	0.58
2018	0.62	0.93	1.13
2019	0.53	0.16	0.88

Source: Obanco (2019) [17]

1.3. Bioenergy in Ecuador

1.3.1. Ethanol

The first attempts at developing the Ethanol Industry in Ecuador started in 2004 mainly focused on exports driven by private initiatives. In that year, the Executive Decree No. 1303 [18] created the biofuels council intended to implement a fuel blend composed of

10% ethanol anhydrous and 90% gasoline for the entire country. This plan sought to replace a percentage of high-octane naphtha imports. To implement the program, it was projected an average production of 1,599,261 barrels of sugar cane derived anhydrous ethanol per year or 650,000 litres/day. To achieve these numbers it was projected to implement 50,000 new hectares of sugar cane crops nationwide [19]. A pilot project was designed to be executed in Guayaquil city. Nevertheless, because of infrastructural problems and technological adjustments, the plan did not start until 2010.

Finally, in January 2010 it was launched Ecopaís program to start the distribution of biofuel in Guayaquil city. Despite having three main private alcohol industries in Ecuador, just one (SODERAL) provided the program's total amount of ethanol. Since the beginning of the pilot project, there have been 52,771.025 gallons of anhydrous ethanol as biofuel in Ecuador[17]. Figure 1 shows the increase in ethanol production for Ecopais in Ecuador during the last 5 years.

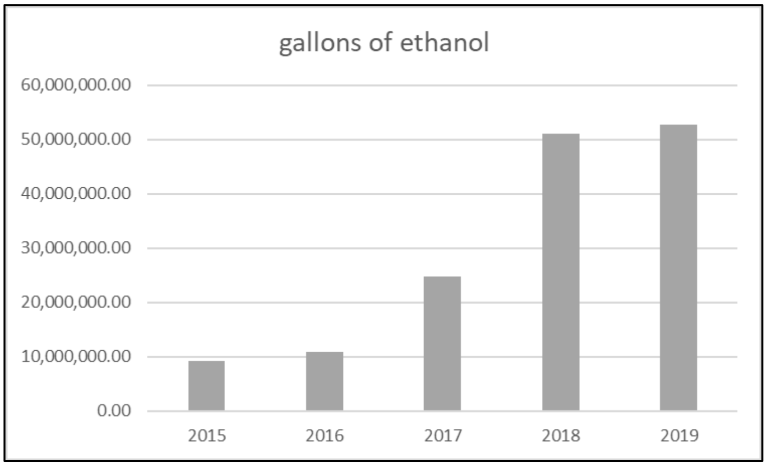

Figure 1. Ethanol production in Ecuador

Source: Petroecuador (2019) [20]

Currently, 375 service stations are authorized to sell Ecopais gasoline in Guayas, Los Ríos, Bolívar, Manabí, Santa Elena, El Oro, Loja, Esmeraldas, Imbabura, and Zamora Chinchipe provinces. In 2019 Ecopais was the best-selling fuel in Ecuador; 50% of gasoline stations in the country sold the fuel [20].

1.3.2. Biodiesel

Executive Decree No. 1303 from September 2012 states that premium diesel fuel used in the country must contain biodiesel from vegetal oil of national production. Article No 3 established a deadline of 8 months from the sign of this Decree (mid-June 2013) for applying the distribution and commercialization of a 5% biodiesel mixture in premium diesel sold in the country. Nevertheless, to date, any formal commercial project has been implemented in the country.

The main oleaginous commodity of Ecuador is palm oil. In Ecuador, the crop contributes 4% of the agricultural gross domestic product (GDP). The production of this commodity presented an annual growth of 8%, from 2010 to 2016, becoming the seventh agricultural export and one of the most dynamic industries of the country. In the last 5 years, 42% of palm oil produced in Ecuador was consumed internally, while 58% was exported for 271,000,000 USD. Ecuador is the twelfth palm oil exporter worldwide as shown in Figure 2. Palm oil production in Ecuador accounts for 300,000 hectares with a total investment of 2,2 billion USD and generates 127,000 jobs [21].

According to the Palm oil producers association of Ecuador (FEDEPAL), 78,737 tons, the equivalent to 70,154,667 litres, were exported in 2018 [22].

The only biodiesel exporting experience has been made by LAFABRIL, an Ecuadorian company that ventures in vegetable oil derivatives. LAFABRIL has a license from EPA

(The Environmental Protection Agency of U.S.A) for biodiesel exportation. The company has exported biodiesel to the U.S.A and Perú [23]. In 2013 the company presented its interest in producing biofuel for a B5 (5% biodiesel blend) program when the national program announced by the Government was about to be launched. Nevertheless, the project was not executed.

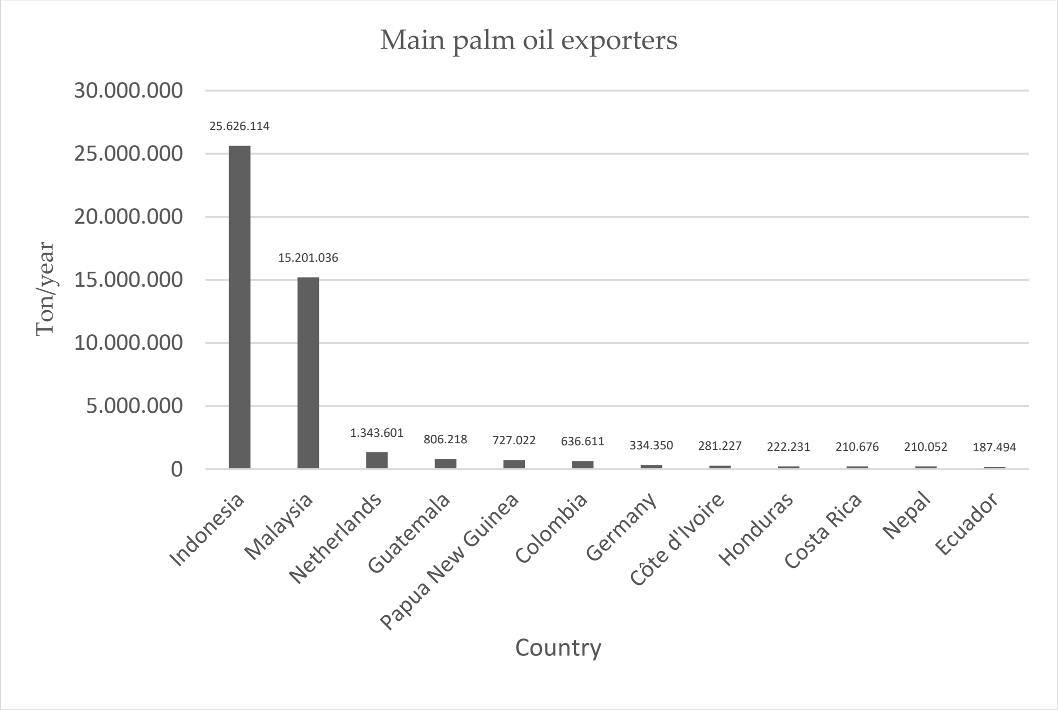

Figure 2. Palm Oil Exports 2019

Source: FAOSTAT (2019) [24]

It must be also highlighted that the Ecuadorian Standards Institute (for its acronyms in Spanish INEN) established the technical standard of normalization for biodiesel with code: NTE INEN 2482-09 to specify the requirements for selling biodiesel in the country.

It must be mentioned that FAO and EIA statistics databases do not present any data for biodiesel production from Ecuador in any year [25].

Finally, the recycling company ARC (recycling cooking oil by its acronyms in Spanish) exports 100,000 litters of waste cooking oil (WCO) monthly to the European Union, where it is converted to biodiesel. The company has 1,800 local clients that provide the resource [26].

1.3.3. Other Biofuels

In 2007, MEER started the project named "Local production of (Jatropha curcas L.) oil from live fences for electricity production in the Galapagos islands." as part of the "Zero Fossil Fuel Initiative for Galapagos" [27]. The project results from the feasibility study for replacing fossil fuels with biofuels for power generation on Floreana Island, hired in 2007 by the United Nations Program for Development, and carried out by the German Development Service, DED. The study recommended using pure vegetable oil derived from Jatropha as the best option for diesel replacement on the island [28].

In 2010, there were installed two dual generators of 69 kW nominal power each on Floreana Island adapted to use vegetable oil as fuel. In the same year, the production of biofuel started with 2,560 gallons of Jatropha pure vegetable oil [27]. To date, 1.08 kBOE have been produced from Jatropha oil [6]. According to MEER, the average pure vegetable oil requirement of Floreana Island for electricity production is around 10,197 gallons per year [29].

1.3.4. Bioelectricity Cogeneration

In Ecuador, the main producers of Energy derived from biomass are the sugar mills that sell electricity derived from sugar cane bagasse combustion to the Ecuadorian electricity interconnected system. The installed capacity of electricity generation of these industries is shown in Table 3 [30].

Table 3. Installed Capacity of Sugar mills companies in Ecuador

Sugar millls companies	Installed capacity (MW)
Agricultural and Industrial Society San Carlos S.A.	73.6
Valdez Sugar Company S.A. (Ecoelectric S.A.)	35.2
La Troncal mill S.A.(Ecudos S.A.)	27.6
Total	136.4

Source: Electrification Master Plan (2018) [30]

According to OLADE, the annual production of electricity nationwide from biomass using thermal processes is shown in Figure 3 [12].

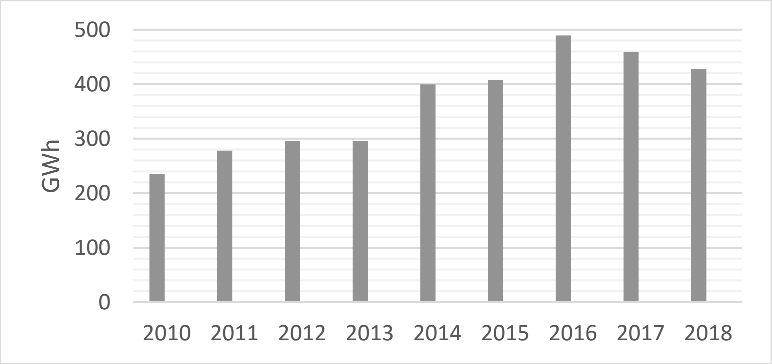

Figure 3. Annual production of electricity from biomass sources in Ecuador

Source: Author, elaborated with data from OLADE (2019) [12]

In 2018, 1.4 million tons of cane bagasse were produced, from which 75.1% was destined for industrial use, while the remaining 24.9% was used for electricity generation. In comparative terms, cane bagasse production decreased by 13.9% between 2017 and 2018 [6].

1.3.5. Energy potential from main agricultural byproducts

The Bioenergy Atlas of Ecuador developed by MEER on 2015 [7], addressed the energy cogeneration potential of the main agricultural residues in Ecuador. Table 6 shows the results in tons and gross energy production.

Table 4. Gross energy potential of byproducts from main agricultural commodities in Ecuador

Product	Production (t/year)	Gross energy (TJ/year)
Cocoa	2,014,727.89	13,627.22
Palm oil	6,841,709.35	87,442.32
Banana	4,890,955.20	61,750.24
Corn	349,254.47	4,355.08
Platain	284,291.00	3,589.29
Rice	2,101,948.94	28,293.09
Total	16,482,886.85	199,057.23

Source: Bioenergy Atlas of Ecuador [7]

1.3.6. The energy potential of biogas from livestock production

The Bioenergy Atlas of Ecuador studied the energy potential based on methane production of the main livestock in the country [7]. The method used for its energy evaluation estimates the number of volatile solids (SV) contained in animal excreta, which have the potential ability to produce methane gas up to a specific limit that is defined for each type of animal. This limit is calculated using a factor called FCM (Methane Conversion Factor). An average value of 0.2 has been adopted for the FCM, which takes into account the climatic conditions of Ecuador and the performance of the facilities (taking as a reference the study carried out by the EPA in 1999 "Livestock Manure Management" [31]. To determine the energy potential in terajoules, the lower calorific value of methane was considered. Table 5 shows the results in tons and gross energy production.

Table 5. Gross Energy Potential of main animal byproducts in Ecuador

Product	Production (t/year)	Gross energy (TJ/year)
Milk cows	323,234.46	64.37
Poultry	80,899.34	0.10
Pigs	9,180.68	9.32
Total	413,314.49	73.78

Source: Bioenergy Atlas of Ecuador [7]

1.3.7. Landfill Gas

Landfill gas (LFG) is a natural byproduct of the decomposition of organic material in landfills. LFG comprises roughly 50% methane (the primary component of natural gas), 50% carbon dioxide (CO2), and a small amount of non-methane organic compounds. When municipal solid waste (MSW) is deposited in a landfill, it undergoes anaerobic decomposition stage when little methane is generated. Then, typically within less than one year, anaerobic conditions are established, and methane-producing bacteria begin to decompose the waste and generate methane [32].

Few experiences of energy recovery using landfill gas have been developed in Ecuador. In 2007, a feasibility study was conducted for the Municipal Public Company of Waste Management of Cuenca city in the landfill of Pichacay. The results of this study showed that by the year 2025, it is estimated that the volume of methane produced by the landfill will be up to 1132 m3/h (50% of CH4). The mentioned study lead to the implementation of the project 1 MW of installed capacity project that produces electricity for 3500 homes [33].

In 2011 the production of landfill gas started in Ambato city on Chachoan landfill. Since then, about 0.058 m3/second of methane gas are produced, generating 12 kW [34]. Furthermore, in Quito city, the landfill El Inga burns methane as a way to reduce greenhouse gas emissions. The program started on January 8, 2011, aiming to credit carbon credits by burning methane; a total of 200,000 certificates of Clean Developments Mechanisms (CDM) were planned to be sold (One certificate per ton) [33].

In 2015 the Latin American Development Bank (CAF by its acronyms in Spanish) started a program focused on reducing methane emission in landfills in Ecuador. The program seeks to pay a determined amount per ton of CO_2 equivalent mitigated. Table 6 indicates the cities with the greatest mitigation potential [33].

The first city to join the program is Guayaquil in December 2019, Ambato, Portoviejo and Santo Domingo municipalities to join the initiative during 2020.

Table 6. Landfill methane mitigation potential by city in Ecuador

City	Municipal solid waste (t/day)	CH_4 emissions (t/5 years)	CH_4 emissions reduction potential (t/5 years)
Guayaquil	2,374	6,510,549	2,932,319
Quito	1,777	3,994,232	1,816,573
Esmeraldas	89	377,170	232,958
Santo Domingo	276	355,300	227,392
Machala	159	288,840	184,857
Ibarra	107	422,382	181,388
Ambato	170	285,835	137,201
Cuenca	325	528,187	124,428
Loja	120	236,116	113,640
Portoviejo	151	236,750	108,772
Duran	132	169,955	95,985
Otavalo	39	199,968	92,826
Quevedo	137	150,619	92,826

Source: Author with data from CAF (2015)

1.3.8. Waste to Energy (Thermal)

Regarding the management of municipal solid waste, the inherent entities solely focus on the implementation of landfills. Moreover, in the country, there is not a legal framework that promotes the exploitation of solid wastes. Nevertheless, some research has been performed such as Waste-To-Energy Incineration: Evaluation of energy potential for urban domestic waste in Guayaquil presents a daily energy potential of 2.48 TJ for incineration 1.80 TJ for methane production by anaerobic digestion for the mentioned city [35].

1.3.9. Firewood

In 2018 firewood accounted for the 2,6% and 11,2% of the energy demand in the industrial and residential sectors, respectively [36]. From 2008 to 2018, firewood use has decreased in 28,6% with 2,400 to 2,000 BOE respectively. The use of firewood with energy ends is responsible for 3% of the total GHG emissions of the energy sector of Ecuador [6]. The total use of firewood nationwide is 8,448,802 m3/year, Figure 4 explain the distribution among provinces. The national average household firewood consumption is 6.37 m3 per family per year, equivalent to 4 tons. It is important to highlight that only 430.60 hectares of forest area affected by firewood consumption in Ecuador, representing around 1% of the total 47,497 hectares deforested annually throughout the country [37]. It must be mentioned the inexistence of regulations regarding the use of firewood in Ecuador.

Firewood combustion is linked to air pollution, which is considered an important source of public health hazard because of the emission of harmful pollutants related to increased risk of respiratory tract infections and lung cancer [38]. Emissions from biomass burning are a major global source of particulate matter and gaseous pollutants to the atmosphere. Combustion of biomass could be responsible for approximately 45% of the total emission of black carbon (BC) to the atmosphere, which is highly effective in absorbing solar radiation [39].

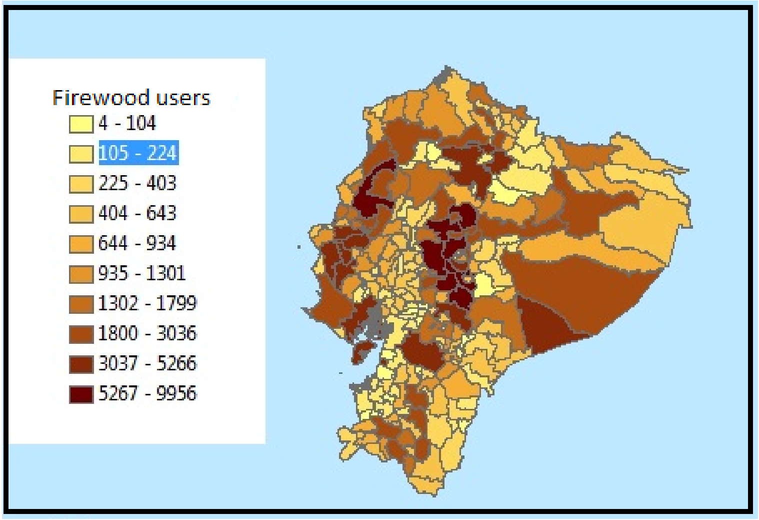

Figure 4. Consumption by householder of firewood in metric tons per canton in Ecuador

Source Author with data from INEC [40]

1.4. Bioenergy research in Ecuador

An overview of the peer-reviewed journal publications was conducted to identify the main research areas in bioenergy in Ecuador in the last 10 years. The Indexed journal database used was Scopus, also, other academic sources were consulted to have a broader scope of the publications in the field. The keywords used for the search were bioenergy, biomass, biofuel, biogas, ethanol, biodiesel, energy, and Ecuador.

In total, 40 publications were found in the following areas: Biomass production, cooking biomass, environmental impact, Policy, liquid biofuels, waste to energy, heat and electricity production, and hydrogen generation. Table 7 shows the studies, their classification, journal, and affiliation.

Table 7. Bioenergy studies develop in Ecuador during the last 10 years

#	**Title**	**Source**	**Classification**	**Journal**	**Filiations**
1	Comparison of the methane potential obtained by anaerobic co-digestion of urban solid waste and lignocellulosic biomass	[41]	Biogas	Energy Reports	Technical University of Machala
2	Biogas from anaerobic co-digestion of food waste and primary sludge for cogeneration of power and heat	[42]	Biogas	Energy Procedia	Newcastle University
3	Viability of Biogas Production and Determination of Bacterial Kinetics in Anaerobic Co-digestion of Cabbage Waste and Livestock Manure	[43]	Biogas	Waste and Biomass Valorization	Universidad Estatal de Bolívar, Universitat Politècnica de València
4	Complete characterization of pruning waste from the lechero tree *Euphorbia laurifolia L.* as raw material for biofuel	[44]	Biomass Production	Renewable Energy	Universidad Politecnica de Valencia, Universidad Estatal de Bolívar,
5	Evaluation of pruning residues of *Ficus benjamina* as a primary biofuel material	[45]	Biomass Production	Biomass and Bioenergy	Universidad Católica de Santiago de Guayaquil
6	Thermoeconomic analysis of integrated production of biochar and process heat from quinoa and lupin residual biomass	[46]	Biomass Production	Energy Policy	University of Aveiro, INER, Instituto Nacional de Investigaciones Agropecuarias INIAP
7	Cocoa residues as viable biomass for renewable energy production through anaerobic digestion	[47]	Biomass Production	Bioresource Technology	Ghent University, Universidad de las Fuerzas Armadas ESPE

#	Title	Source	Classification	Journal	Filiations
8	Energy and carbon footprints of ethanol production using banana and cooking banana discard: A case study from Costa Rica and Ecuador	[48]	Biomass Production	Biomass and Bioenergy	Centre de Cooperation Internationale en Recherche Agronomique pour le Developpement (CIRAD), Cooperativa de Caficultores de Dota (Coopedota), Escuela Superior Politécnica del Litoral (ESPOL)
9	Dendrometric characterization of corn cane residues and drying models in natural conditions in Bolivar Province (Ecuador)	[49]	Biomass Production	Renewable Energy	Universidad Estatal de Bolívar, Universidad de Carabobo, Universidad Politécnica de Valencia
10	Characterization of teak pruning waste as an energy resource	[50]	Biomass Production	Agroforestry Systems	Universidad Catolica de Santiago de Guayaquil, Universitat Politécnica de Valencia
11	Study of the influence of starch as binder material for Ecuadorian cocoa pod husk pellets	[51]	Biomass Production	Other	University of Guayaquil
12	A preliminary study of pelletized Ecuadorian cocoa pod husk for its use as a source of renewable energy	[52]	Biomass Production	Other	University of Guayaquil
13	Microwave Pyrolysis Process Potential of Waste Jatropha Curcas Seed Cake	[53]	Biomass Production	Chapter	IIGE
14	Design and Analysis of a Hybrid Drying Using Renewable Technologies	[54]	Biomass Production	Other	Escuela Superior Politécnica del Litoral (ESPOL), Santiago of Compostela University
15	Prediction models based on higher heating value from the elemental	[55]	Biomass Production	Journal of Renewable and	Universidad Católica de Santiago de Guayaquil,

#	Title	Source	Classification	Journal	Filiations
	analysis of neem, mango, avocado, banana, and carob trees in Guayas (Ecuador)			Sustainable Energy	Universidad de Almería, Universidad Politécnica de Valencia
16	Structure analysis and biomass models for plum tree (*Prunus domestica l.*) In Ecuador	[56]	Biomass Production	Other	Universitat Politècnica de Valencia, Universidad Técnica del Norte
17	Analysis of energy, CO2 emissions and economy of the technological migration for clean cooking in Ecuador	[57]	Cooking Biomass	Energy Policy	IIGE Universidad Internacional SEK, Centre Internacional de Mètodes Numèrics en Enginyeria (CIMNE)
18	In-situ energy and security evaluations of wood stoves in the High Andean region of Ecuador	[58]	Cooking Biomass	Other	Escuela Superior Politécnica de Chimborazo
19	Relationship of pulmonary function among women and children to indoor air pollution from biomass use in rural Ecuador	[38]	Cooking Biomass	Respiratory Medicine	Purdue University, University of Azuay, Indiana University, Columbia University
20	Life cycle assessment of second-generation ethanol derived from banana agricultural waste: Environmental impacts and energy balance	[59]	Environmental Impact	Journal of Cleaner Production	Universidad Politécnica de Madrid, Universidad Andres Bello
21	Residual biomass-based hydrogen production: Potential and possible uses in Ecuador	[60]	Hydrogen Production	Hydrogen Energy	Universidad de Santander, Universidad de Cuenca, Universidad Central del Ecuador, IIGE
22	Preliminary estimation of electrolytic hydrogen production potential	[61]	Hydrogen Production	International Journal of Hydrogen Energy	Universidad de Cuenca, Universidad de Los Andes

#	Title	Source	Classification	Journal	Filiations
	from renewable energies in Ecuador				
23	Energy use of Jatropha oil extraction wastes: Pellets from biochar and Jatropha shell blends	[62]	Heat / Electricity	Journal of Cleaner Production	IIGE, Centre Internacional de Mètodes Numèrics en Enginyeria (CIMNE), Universidad Regional Amazonica Ikiam
24	Energetic valorization of the residual biomass produced during Jatropha curcas oil extraction	[63]	Heat / Electricity	Renewable Energy	University of Aveiro, IIGE
25	Thermal Evaluation of a Hybrid Dryer with Solar and Geothermal Energy for Agroindustry Application	[64]	Heat / Electricity	Applied Sciences	Escuela Superior Politécnica del Litoral, ESPOL, Universidad Técnica de Ambato, Universitat Politècnica de València
26	Analysis of Combined Biochar and Torrefied Biomass Fuel Production as Alternative for Residual Biomass Valorization Generated in Small-Scale Palm Oil Mills	[65]	Heat / Electricity	Waste and Biomass Valorization	University of Aveiro
28	Fast pyrolysis of mannan-rich ivory nut *Phytelephas aequatorialis* to valuable biorefinery products	[66]	Liquid Biofuels	Chemical Engineering Journal	Ghent University, University of Hohenheim
29	DFT modelling of ethanol on BaTiO3(0 0 1) surface	[67]	Liquid Biofuels	Applied Surface Science	Universidad Técnica Particular de Loja
30	GIS-Based Assessment of Banana Residual Biomass Potential for Ethanol Production and Power	[68]	Liquid Biofuels	Waste Biomass Valorization	Universidad Politécnica de Madrid

#	Title	Source	Classification	Journal	Filiations
	Generation: A Case Study				
31	Estimating the potential and planning of bioethanol production from agro-residues based on a model-predicted NPP under climate change in Ecuador	[69]	Liquid Biofuels	Journal of Agricultural Meteorology	Osaka University
32	Nation-wide planning of agro-residue utility for bioethanol production and power generation in Ecuador	[70]	Liquid Biofuels	Energy Procedia	Osaka University
33	Optimizing plant allocation for bioethanol production from agro-residues considering CO2 emission and energy demand-supply balance: A case study in Ecuador	[71]	Liquid Biofuels	Waste Biomass Valor	Osaka University
34	Feasibility assessment of waste banana peduncle as feedstock for biofuel production	[72]	Liquid Biofuels	Biofuels	Escuela Superior Politécnica del Litoral (ESPOL), University of Florida
35	Modelling of Production and Quality of Bioethanol Obtained from Sugarcane Fermentation Using Direct Dissolved Sugars Measurements	[73]	Liquid Biofuels	Energies	Universitat Politècnica de Valencia, Universidad Estatal de Bolívar
36	Composting as a sustainable strategy for municipal solid waste management in the Chimborazo Region, Ecuador: Suitability of the obtained composts for seedling production	[74]	Municipal Solid Waste to Energy	Journal of Cleaner Production	Escuela Superior Politécnica de Chimborazo, Universitat Politecnica de Catalunya

#	Title	Source	Classification	Journal	Filiations
37	Use of Municipal Solid Waste (MSW)-Derived Hydrogen in Ecuador: Potential Applications for Urban Transportation	[75]	Municipal Solid Waste to Energy	Waste and Biomass Valorization	Universidad de Santander, INER, Universidad de Cuenca, Universidad Central del Ecuador
38	Waste-To-Energy Incineration: Evaluation of energy potential for urban domestic waste in Guayaquil	[35]	Municipal Solid Waste to Energy	Iberian Journal of Information Systems and Technologies	Universidad de Guayaquil, Escuela Superior Politécnica del Litoral (ESPOL)
39	Palm oil kernel shell as solid fuel for the commercial and industrial sector in Ecuador: tax incentive impact and performance of a prototype burner	[76]	Energy Policy	Journal of Cleaner Production	University of Aveiro, IIGE
40	Synergies between agriculture and bioenergy in Latin American countries: A circular economy strategy for bioenergy production in Ecuador	[77]	Energy Policy	New Biotechnology	Technical University of Machala, Technical University of Madrid

In terms of affiliation, the major number of publications belongs to the National renewable and energy efficiency research institute (INER by its acronyms in Spanish) which changed its name on 2016 to the National geologic and energy research institute (IIGE by its acronyms in Spanish), the predominant national universities performing bioenergy research are Escuela Superior Politécnica del Litoral (ESPOL), Universidad Católica de Santiago de Guayaquil and University of Guayaquil, regarding international universities the Universitat Politècnica de Valencia, the University of Aveiro and the University of Osaka count with 3 studies each. Figure 5 shows the number of publications by affiliation.

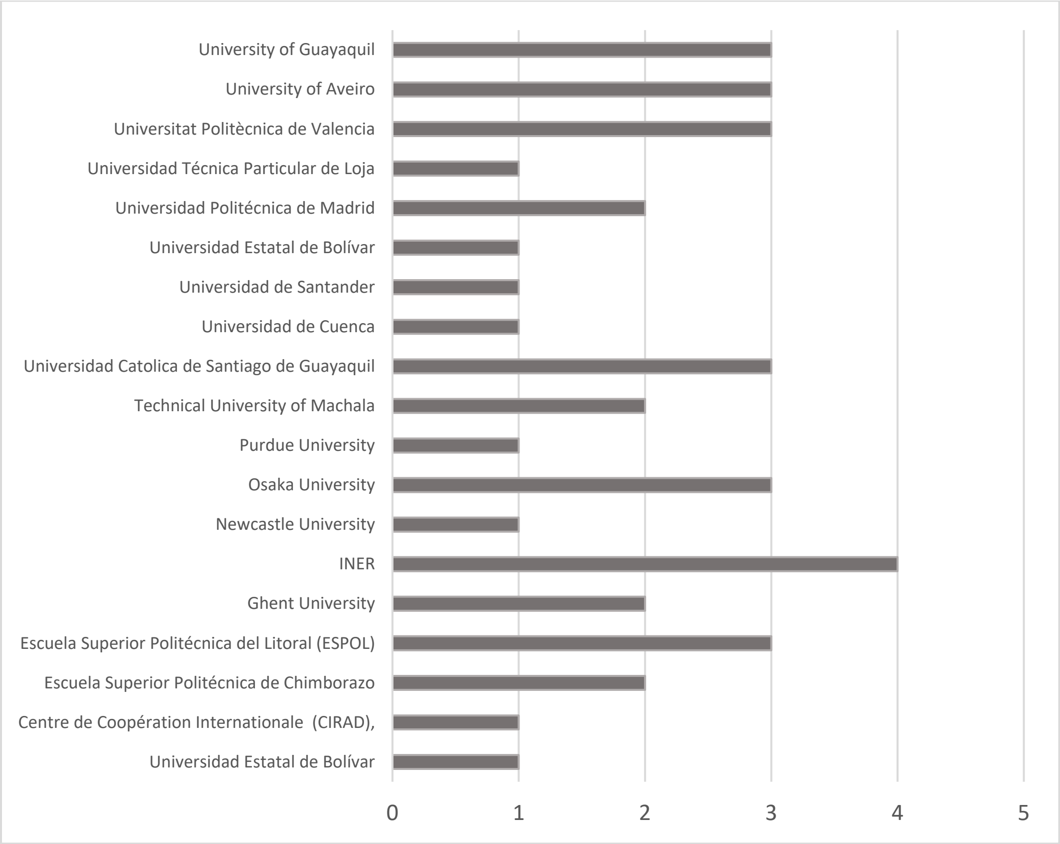

Figure 5. Number of bioenergy publications in scientific journals by filiation in Ecuador 2010-2020

Most bioenergy studies in Ecuador focused mainly on residual byproducts of important agricultural commodities.

The proportion of papers focusing on residual biomass exploitation to produce heat and electricity is much higher than the rest. On the other hand, local legislation has influenced research decision-making. In this regard, topics with a legislative incentive as biofuels are relevant.

Finally, it is important to remark that in the last years, research in nontraditional areas as Hydrogen production from bioenergy processes has begun to appear.

1.5. Research problems and hypothesis

In Ecuador, although hydropower remains the most cost-effective and low emission energy source for the long-term in the power sector of Ecuador, constraints on its deployment and uncertainty around climate change impacts could compromise its ability to contribute to addressing climate change targets, in this regard it is crucial to increase the share of alternative sources like natural gas, biomass and geothermal energy to provide both peak and baseload generation in low runoff seasons [78]. Further research on environmental impacts of future energy scenarios has determined that due to the increasing demand the global warming potential of the net electricity generation in Ecuador will increase from 12 to 20 times by 2050 over 2016 [79]. Besides, studies have found that if ecological system losses are integrated into a conventional hydropower cost assessment the generation costs would be significantly higher [80].

The electrification Master plan of Ecuador considers that the maximum power generation from agricultural waste biomass could be 12.7 TWh/year by 2025 (equivalent to a firm capacity of 500 MW) [30].

Furthermore, as in most islands, electricity generation in the Galapagos is heavily based on fossil fuels. According to its energy balance, 89% of the electricity produced in the islands comes from fossil fuels, 8.2% from wind, 2.5% from solar and 0.1% from biofuels [81]. Also, Galapagos has endured severe environmental, and economic impacts from fossil fuel spill on its marine reserve.

According to the above mentioned, there is a prevailing necessity to explore new bioenergy options to support future energy demand.

In this regard, the hypotheses of this work were:

- There are environmental advantages of electricity produced from waste cooking oil vs. refined palm oil in Galapagos Islands.
- There exists available land in Continental Ecuador to produce second-generation dedicated energy crops for electricity production.

1.6. Objectives

1.6.1. General objective

The general objective of the research is to identify potential second-generation bioenergy feedstocks for continental Ecuador and Galapagos islands using environmental evaluation tools and geographical information systems.

1.6.2. Specific objectives

The specific objectives were separated for each research topic. Specific objectives are presented below.

In Life Cycle Assessment of Bioenergy in Islands:

- Evaluate the environmental performance of two bioenergy alternatives for firm electricity production in Galapagos islands: a) imported refined palm oil (RPO), and b) locally produced clean waste cooking oil (WCO), using Life Cycle Assessment methodology.
- To measure emissions derived from the production of electricity from waste cooking oil and refined palm oil.

In the Agroecological Zoning of second-generation energy crops:

- Identify suitable energy dedicated crops suitable for cultivation in Ecuador.
- Identify suitable areas for the agricultural production of dedicated second-generation energy crops.
- Determine the energy potential of resulting energy crops to be produced in Ecuador.

1.7. Methodology overview

Two different methodologies were used to identify bioenergy alternatives for Ecuador. The methodological approaches used are described below.

1.7.1. Life Cycle Assessment of Bioenergy in Islands

The Life Cycle Assessment was performed following the ISO 14040 standard [82]. Data used were primarily obtained from processes studied, but to some extent, generic LCA data was used, e.g. for the use of fuels in energy supply and transports, while emissions and electricity generation yield from direct use of RPO and WCO were measured in a test system. The Life cycle impact assessment (LCIA) method used in this study was CML 2001 (baseline) methodology [83]. This methodology uses the damage-oriented approach or endpoint approach for impact assessment. Impact categories considered in this methodology include the following: carcinogens, respiratory organics, and inorganics, climate change, ionizing radiation, ozone layer depletion, ecotoxicity, acidification/eutrophication, land use, minerals, and fossil fuels uses.

Software Simapro version 9.0.033 was used to calculate the impacts determined by the mentioned method. A contribution analysis was performed to understand the contributions of specific processes and pollutants to the total impact scores per impact category and find the reasons for the environmental impacts between RPO and WCO. Processes and materials data were obtained from in situ research.

1.7.2. Agroecological Zoning of second-generation energy crops.

The Agroecological Zones (AEZ) methodology used in this part of the study was developed by the Food and Agriculture Organization of the United Nations (FAO), jointly with the International Institute for Applied Systems Analysis (IIASA) [84].

An agro-ecological zone is defined as homogenous and contiguous areas with similar soil, land, and climate characteristics. The methodology consists on the identification of areas with similar agroecological characteristics taking into account biophysical variables as edaphic texture, depth, precipitation, stony, drainage, salinity, pH, fertility, slope, and climatic requirements like temperature, and precipitation of a determined crop and the conditions given by an ecosystem. This information merge results and obtain limitations and/or potential areas to develop a determined crop [85]. Software QGIS 3.15 and GIS maps at 1:25000 scale were used to perform the study.

1.8. Motivation for the research

Due to the current scarcity of biofuel to supply the demand for electricity generation in Galapagos, low environmental impact alternatives must be identified and promoted. Furthermore, despite Jatropha, any other biofuel alternative for electricity generation on Galapagos island has been studied [86]. On the other side, in terms of zoning studies, the renewable energy potential for variable energy resources as solar [87], wind [88] and both resources [89] have been addressed. Besides, agroecological zoning studies have just been developed mainly for food commodities [90] [91]. In terms of bioenergy resources in Latin America, zoning studies have focused on crop by-products [92], few studies have focused on dedicated bioenergy crops [27,93–95].

As mentioned in the introduction, because of value chain associated difficulties to the use of agricultural residues as an energy feedstock in Ecuador, it is important to explore the feasibility of producing energy dedicated crops to support future climate change mitigation scenarios.

1.9. Innovative aspects of the research

The innovative aspect of the research is the identification of second-generation bioenergy feedstocks for electricity generation in Ecuador through the use of geographical information systems and life cycle assessment methodologies for continental and insular Ecuador in order to contribute to the decarbonization its energy matrix according to NDC goals [96].

The main contributions are cited below:

- A scientific article titled: "An Environmental Comparison of Continental Palm Oil vs. Local Waste Cooking Oil for Electricity Generation" published in the Journal Q2 Applied Sciences, impact factor 2.458 [97].
- Air emissions data acquired by direct experimental measurements of waste cooking oil and refined palm oil combustion for electricity generation. The resulting data was included in the Life Cycle Inventory of the precedent scientific article.

- Use of Geographical Information systems (GIS) to identify potentially available land for second-generation bioenergy dedicated crops in Ecuador. A methodological approach focused on avoiding interfering with agricultural land, anthropic infrastructure and ecological importance biomes was developed.
- Overview of the peer-reviewed journal publications conducted to identify the main research areas in bioenergy in Ecuador during the last 10 years. The Indexed journal database used was Scopus, also, other academic sources were consulted to have a broader scope of the publications in the field

1.10. Thesis structure

The first chapter of this work includes the baseline and justification of the study detailed in the introduction and objectives for each study. The second chapter includes the theoretical background, including the challenges facing bioenergy and the implications in terms of emissions and resource utilization. This chapter also consists of a vision of the challenges that bioenergy faces in isolated systems as Islands. The third Chapter includes the materials and methods used in each of the studies developed. The fourth chapter shows the results in separate sections for each of the studies; maps are included to showcase graphically the results when applicable. The fifth chapter discusses the results and contrasts them with similar studies. The sixth section shows the conclusion and recommendations for further research.

2. Theoretical Background

2.1. Challenges in bioenergy production

A rapid increase in demand for bioenergy production has led to various environmental and socio-economic concerns. It has been linked to the 'global food crisis' and sparked the food versus fuel debate [98]. Land-use change occurs when bioenergy production displaces natural habits, this fact has and will affect severely on the land and resource-abundant developing regions without strong sustainable land use policies [99]. In this section, we explore the main sustainability challenges that bioenergy development faces.

2.1.1. Bioenergy and water footprint

A drawback of bioenergy crops is that they compete with food and use the same natural resources like water. The water footprint (WF) of bioenergy is large compared to other forms of energy [100]. It is more efficient to use total biomass, including stems and leaves, to generate electricity than to produce biofuel. For most crops, the WF of bioelectricity is about a factor of 2 smaller than the WF of bioethanol or biodiesel. This difference is caused by the crop fraction that can be used. For electricity, total biomass can be used; only the starch or oil fraction of the yield can be used for bioethanol or biodiesel. In general, the WF of bioethanol is smaller than that of biodiesel. The WF of bioenergy shows considerable variation, depending on three factors: (i) the crop used, (ii) the climate at the location of production, and (iii) the agricultural practice [101].

The global WF of electricity and heat is estimated at 378 billion m^3 per year. Wind energy (0.2–12 m^3/TJe), solar energy through PV (6–303 m^3/TJe), and geothermal energy (7–759

m^3/TJe) have the smallest WFs, while biomass (50 000–500 000 m^3/TJe) and hydropower (300–850 000 m^3/TJe) present the largest WF [102].

In terms of heat production, studies show that WF from combustion or gasification is similar. WF of electricity by combustion ranges from 33 to 324 m^3/GJ, and the WF of electricity by gasification from 21 to 104 m^3/GJ. From a WF perspective, it seems that it is relatively water-efficient to use crop residues to produce bioenergy and that energy dedicated crops could be less favourable. As an illustrative example, the total WF of residue feedstocks from cassava, sugar beet, sugar cane, wheat, rice, soybean, corn, rapeseed, and cotton ranges between 5 and 67 m^3/GJ. Pine and eucalyptus have the largest WF, between 77 and 491 m^3/GJ. The WF of heat from combustion 5 to 91 m^3/GJ or from gasification 8 to 80 m^3/GJ is similar. The WF range for pyrolysis oil 7 to 213 m^3/GJ is comparable to the range for bioethanol from fermentation 6 to 491 m^3/GJ [100].

Projections suggest that a 100% shift to bioenergy is not possible from water and land perspectives. Conservative scenarios indicate that using the most efficient feedstocks for bioenergy production (sugar beet and sugarcane), it would still require 11 to 14% of the global arable land and a water flow equivalent to 18–25% of the current water footprint of humanity. Using sugar or starchy crops to produce bioenergy results in smaller footprints than using oil-bearing crops in comparative terms. Despite the crop of choice, processing biomass in combined heat and power systems results in smaller land, water, and carbon footprints per unit of energy than when converting to electricity alone or liquid biofuel [103].

2.1.2. Bioenergy and carbon neutrality

Under the current greenhouse gases accounting systems, emissions produced when biomass is burnt for energy are accounted as zero, resulting in what is referred to as the 'carbon neutrality' assumption [104]. This assumption is based on the fact that the amount of CO2 released to the atmosphere when biomass is combusted is equivalent to the amount fixed by the during its production cycle.

Although life cycle assessment studies show a positive carbon balance for most bioenergy feedstocks compared with a fossil fuel alternative base scenario [105,106], compressive research of greenhouse gas emission sources during the production cycle must be performed when bioenergy scenarios are analyzed.

During the agricultural and industrial production stages of bioenergy, some processes contribute to GHG emissions as is described below.

2.1.2.1. Land Use Change

Studies have emphasized the importance of land-use change on the overall GHG balances in biomass production [107, 108]. Land-use change for bioenergy production can occur in the following ways: a) directly, when non-cropland is converted to energy croplands (e.g. grassland is used to plant palm oil for biodiesel), or b) indirectly, when existing food and feed cropland is converted for use as energy crops, thus inducing new production of the food/feed crop elsewhere, at the expense of native habitats, to meet total demand. Second-order effects may also occur (e.g. expanded soybean production in pastureland leads to the conversion of rainforests into pastureland) [105].

The demand for bioenergy is projected to grow as energy and climate policies worldwide promote the use of biomass for climate change mitigation [109]. However, the carbon impacts of forest bioenergy are stressed in the literature. Studies projecting significant roles of forest bioenergy in climate change mitigation scenarios rely on assumptions that are too optimistic and unrealistic.[110].

Varying results in the literature on the role of bioenergy in climate change mitigation have generated a debate that is still on-going [111, 112]. Studies in this matter are polarized, with some of them concluding that forest derived bioenergy increases GHG emissions compared to fossil fuels over a timescale of decades, centuries, or even indefinitely, while others concluded that significant emission reductions can be achieved within reasonably short timeframes [113–116]. This divergence is largely due to different sources of biomass considered and modelling methodologies and assumptions, as biomass carbon content, life cycle analysis boundaries, and carbon soil content among other variables [113,117].

Other studies explore the fact of whether or not the increased bioenergy demand would reduce deforestation and/or drive reforestation efforts [118].

However, if current harvest levels are increased to produce more bioenergy, carbon that would have been stored in the biosphere might be instead released into the atmosphere [119]. Land-use change can produce a negative carbon balance above ground when forests are cleared to produce bioenergy feedstocks, and carbon stored in the soil underground is released to the atmosphere when inadequate agricultural labours are used. In dedicated bioenergy crops, the risk of the short-to-medium term negative impacts is high when additional stocks are extracted to produce bioenergy, and the proportion of biomass used for bioenergy is low, or when land with high C stocks is converted to low productivity bioenergy plantations [120].

Other works have shown negative net carbon balances (around double emissions compared to Natural gas) when biomass depletion occurs in native ecosystems not conceived for energy ends [121].

It is very difficult to model the complex interactions between demand and land-use change in agricultural markets. Hereof, there is an increasing concern that current bioenergy policies do not adequately take into account the risk of GHG emissions occurring indirectly [122]. Furthermore, research has also demonstrated that land use related effects may completely offset the potential GHG emission reduction of bioenergy and substantially increase emissions compared to conventional fuels [123].

On the other hand, most climate change mitigation scenarios, rely on the incremental use of bioenergy, which would significantly increase the international trade of [124–126].In 2015 total global bioenergy trade volumes exceeded 1 EJ/year, of which 60% was directly traded for energy purposes (e.g., biodiesel, wood pellets) and 40% for other purposes where part of the primary bioenergy was used for energy during the final processing (e.g., black liquor and sawdust combustion from imported roundwood) [127].

However, the scaling up of bioenergy trade is projected to take place in the near future, across models, for a scenario likely to achieve a 2 °C target, 10–45 EJ/year out of a total global bioenergy consumption of 72–214 EJ/year are expected to be traded across world regions by 2050. While this projection is greater than the present trade volumes of coal or natural gas, it remains below the present crude oil trade. This growth in bioenergy trade largely replaces the trade in fossil fuels (especially oil), which is projected to decrease significantly over the twenty-first century [128].

Besides, models suggest that Latin America and Africa could be the main net exporting regions, with the EU, the USA, and Asia likely being net importers. In this regard, the large volumes of bioenergy traded may have significant implications concerning potential revenue sources, economic development, and trade imbalances. Given that increased bioenergy trade may lead to significant land-use changes in supplying countries. [110,128]

Finally, the estimation of direct life-cycle GHG emissions reductions from crop-based bioenergy production and use is also a complicated task, requiring knowledge and assumptions about baseline landscapes, carbon stocks, land management, and how fossil fuel and biofuel production interact and influence these and other variables. Indirect land-use change is a critical fact to consider (ILUC) in places distant from the bioenergy production sites [129,130].

2.1.2.2. Change in the soil carbon stock

Soil carbon is a dynamic and integral part of the global carbon cycle. It has been a source of atmospheric carbon dioxide (CO_2) since the beginning of settled agriculture, depleting more than 320 billion metric tons (Pg) from the terrestrial pool, 78±12 Pg comes from the soil. In comparison, approximately 292 PgC have been emitted through fossil-fuel combustion since about 1750.

Terrestrial carbon pools have been drastically altered by human activities (deforestation, biomass burning, soil cultivation, drainage of peatlands) since the dawn of settled agriculture about 10,000 years ago [131].

Cropping reduces soil organic carbon content mainly due to low organic matter input and accelerated decomposition with tillage [132].

Approximately 70% of the plant is above ground, and 30% in the soil in most herbaceous energy crops. In forests, though, the biomass above ground composes about 45% of the organic storage [133]. When the crop is harvested, the root system starts to decompose, releasing carbon into the soil. The amount of carbon release is dependent on the soil type and structure, precipitation, landscape, and other biotic and abiotic factors [114]. Nevertheless, compared with conventional commodity crop rotations, tillage practice is reduced in most biomass crop production. This leads to more carbon being fixed in the root system and more organic matter stored in the soil [134].

2.1.2.3. Nitrogen fertilization

Although N fertilizer can increase biomass production, its use has a direct impact on greenhouse gas (GHG) contributions of bioenergy production substantially: not only through the production, transportation, and distribution of the fertilizer itself but also through fertilizer-induced microbial emissions of nitrous oxide (N_2O), a GHG with a global warming potential around 300 times that of carbon dioxide [135].

Also, nitrogenated fertilizer lost to the environment as nitrate NO_3 leads to indirect emissions of N_2O elsewhere in downstream surface waters [136]. Additionally, well-aerated soils are a globally significant sink for atmospheric methane (CH_4), and ammonium (NH_4) [137]. N fertilizers can competitively inhibit microbial CH_4 oxidation [138,139]; the incremental use of N fertilizer inputs can substantially reduce and even eliminate the climate benefit of food crops grown for bioenergy [140]. Nevertheless, Crops with less N demand, such as grasses and woody coppice species, have more favourable climate impacts [141].

2.1.2.4. Use of fossil fuels in transport and processing

The use of fossil fuels in the life cycle production of bioenergy can significantly increase its GHG footprint. Fossil fuels are used in industrial processes, transport, and agricultural machinery, among other uses. In this regard, it is important to consider efficacy measurements as adequate logistics, short travel distances, and energy efficiency improvements.

2.1.2.5. Inputs and capital goods

Greenhouse gas emissions are also derived from the production of different inputs used in agricultural production of bioenergy feedstocks as fertilizers, pesticides, herbicides, and seeds. Normally, life cycle inventories aggregate all emissions involved in the production phase of inputs as the use of raw materials and semi-finished products, process energy, and transport of raw materials and intermediate products. Inventories are calculated from values measured in local production plants [142].

On the other hand, GHG are also emitted during the construction of infrastructure and machinery used in the agricultural production of biomass. This category includes buildings, infrastructure construction and operation, machinery, construction, and work processes [143].

2.1.3. Bioenergy combined with carbon capture and storage (BECCS)

Bioenergy with carbon capture and storage is the combination of two well-known technologies for climate change mitigation. Carbon capture and sequestration (CCS) to mitigate CO_2 emissions and the use of biomass as an energy source. Their combination is identified as a negative emission technology (NET) [144]. Negative emissions occur because biomass captures CO_2 during photosynthesis as described in the previous section, and emissions occurring during its energy conversion are captured and stored.

World energy prospective models under climate change mitigation scenarios indicate that the large-scale deployment of biomass (>200 EJ), together with BECCS, could help to keep global warming below 2° degrees of preindustrial levels. Nevertheless, the high deployment of land-intensive bioenergy feedstocks could also lead to detrimental climate effects, negatively impact ecosystems, biodiversity and livelihoods, for this reason, sustainability approaches must be taken into account [145].

The application of CCS in power plants involves three main stages. These include CO2 separation from the power plant stream or simply carbon capture (CC), transportation of the captured CO2, and finally, CO2 sequestration.

On the other hand, world cumulated storage capacities assumed in model TIAM-FR, developed under the IEA's Energy Technology Systems Analysis Program, are 14,800 Gt of CO2 with 12,600 Gt of CO2 that can be stored in deep saline aquifers. The total potential for Central and South America 15,78 Gt CO2, 99% correspond to deep saline aquifers [146]. Table 8 shows the capacity per storage type at global and regional levels.

Table 8. Carbon dioxide storage capacity

	Enhanced oil recovery	**Depleted oil fields (onshore)**	**Depleted oil fields (offshore)**	**Depleted gas fields (onshore)**	**Depleted gas fields (offshore)**	**Enhanced coalbed methane recovery < 1000 m**	**Enhanced coalbed methane recovery > 1000 m**	**Deep saline aquifers**	**Total**
World	153.50	225.50	51.55	821.00	209.50	358.75	358.75	12,648.00	14,826.55
Center and South America	15.00	15.00	3.00	45.00	0.00	0.00	0.00	1,500.00	1,578.00

Source: Author with data from Ricci et al. 2013 [146]

Carbon Capture technologies can be classified in the following groups:

a) **Economically feasible under specific conditions.**

Post-combustion carbon capture: This technology separates CO_2 from flue gases produced from large-scale fossil fuel combustion sites like boilers, cement kilns, and industrial furnaces. Today absorption process using chemical solvents like amine is often used in the CC from several power plants. The hot flue gas is then cooled to temperatures between 40 and 60 °C and introduced to the absorber, where CO_2 bonds with a chemical solvent. The CO_2 rich solvent is then pumped to a stripper where the solvent is heated for solvent regeneration between 100 and 140 °C, and CO2 is stripped off [147].

Pre-combustion carbon capture: This technology involves syngas (a mixture of H_2 and CO produced from fuel reforming followed by CO_2 separation. Fuel reforming and partial oxidation are the major processes that lead to the formation of the synthesis gas. In steam reforming, steam reacts with fuel in a partial oxidation reaction [148].

Geological sequestration of CO_2. This technique considers capturing CO_2 directly from the sources and its disposal into geological formations for some time. Many approaches can be adopted for the capture of CO_2 in geologic formations. A low permeable geological medium is first used to capture supercritical CO_2 at the initial stage, where a reaction between CO_2 and the solid occurs. This is then followed by solubility trapping, where the CO_2 is absorbed into the water phase, with the reaction occurs directly or indirectly [149]. There exist three options. The first has to do with using active as well as depleted oil and gas fields for the recovery of oil and gas, in which it helps for carrying out enhanced oil or gas recovery. The next option has to do with deep unmineable coal layers capable of enhancing methane recovery called Enhanced coalbed methane recovery. The last option is deep saline aquifers. These storage techniques have been used in the past for storing oil and gas at a cheaper rate, which can equally be applied to CO_2 storage [150].

b) Research phase.

Physical absorption, Carbon dioxide separation for post and pre-combustion CC occurs in two steps: absorption and stripping process. In absorption, the gas stream is fixed physically with the solvent stream. In the stripping process, the CO_2 rich solvent is heated to regenerate the solvent and strip off CO2gas. The main principle in physical CO_2 absorption is Henry's law. In the absence of any form of alteration of chemical identities of CO_2 and the solvent, the breakdown of CO_2 in the liquid solvent is due to the electrostatic interaction or Vander Waals attraction forces [148].

c) **Demonstration phase.**

Oxyfuel combustion: The oxy-fuel combustion process includes burning fossil fuel in pure oxygen, leading to nitrogen-free flue gas production with only CO_2 and H_2O. The flue gas condensation leads to a pure CO_2 stream being produced, as well as the elimination of NOx gases [149].

2.1.4. Second generation energy crops

Significant social and environmental issues associated with first-generation based bioenergy feedstocks have emerged in the last years [151]. Incremental demand for food and feed-based crops to produce biofuels has contributed to increased food prices threatening food security [152]. In response to such emerging issues, the European Union (EU) has proposed a significant policy shift that would reduce the use of first-generation feedstocks from 10% to 5% [153]. Furthermore, the instrument sets that greenhouse gas emission savings from the use of biofuels and bioliquids shall be at least 60 % for new greenfield installations and incremental savings from 35 to 50% for brownfield installations. Besides, the policy encourages developing a second-generation dedicated lignocellulosic feedstock industry [153].

Second-generation bioenergy feedstocks are defined as the ones produced from nonedible crops including the agricultural waste, dedicated energy crops, wood chips, waste cooking oil, and municipal solid waste. For example, wheat straw from wheat production and corn husks from corn cultivation are second-generation feedstock [154].

An essential characteristic of second-generation feedstocks is their abundance, low cost, and energy output to input ratio. These are lignocellulosic materials that make up the fibrous and woody structural components of plants. The herbaceous and woody species being targeted for development as lignocellulosic crops are robust perennial species that can resprout from rootstocks after harvest. Additionally, studies have shown that woody crops can provide ecosystem services and, therefore, complement rather than compete with conventional agriculture[155].

2.2. Bioenergy in islands

The energy share of most islands is highly dependent on imported fossil fuels, which exposes them to volatile oil prices, limits economic development, and degrades local natural resources. On average, 88% of the total electricity demand in small island developing states (SIDS) is met by fossil fuels. In comparison, the remaining 12% is supplied primarily by hydropower, followed by wind energy and biomass in lower proportions [156]. As an illustrative example, in the island countries of the Caribbean Community (CARICOM), 89.7% of the total installed electricity capacity corresponds to fossil fuel technologies, and just 10.2% comes from renewables [157]. Besides, between the years 2000 and 2015, the average energy intensity (total energy consumption/GDP) in islands has increased by 23.4%, with a corresponding emission intensity (total emissions/GDP) increase by 12.4% [158]. This ongoing energy dependence fails to establish a precedent for global action to mitigate the long-term consequences of climate change, which pose a particularly acute threat to islands.

From 2010 the number of peer-reviewed publications about renewable energy in islands has multiplied by three mainly because of the special attention that some intergovernmental organizations (like the Intergovernmental Panel on Climate Change) have given to island nations as they recognized their vulnerability to climate change [159].

Most studies have focused on a variable rather than base renewable energy resources as biomass. Surroop et al 2018 [159] identified 41 studies published focused on wind, solar and ocean-based technologies and just 12 studies about bioenergy in small island developing states (SIDS) during the 2010-2017 period.

Studies regarding the potential use of alternative biomass feedstocks for energy production in islands are topic diverse as biodiesel production on Crete island [160], coconut oil electricity generation in the pacific islands [161], biogas production from animal waste in Indonesia [162], forest waste-derived fuel with waste cooking oil in Taiwan [163], biogas from animal manure in the Canary Islands [164], biomass-fueled combined heat power (CHP) in Åland Islands [165], Perennial tree pruning biomass for electricity generation in Greece [166]. Biomass research in Ecuador has addressed the energy potential of some residues from important agricultural commodities [44,45,49,53]. Some authors have also studied liquid and gaseous biofuel potential generation [43,48,71,73].

There are some efforts in many SIDS for using biomass to contribute to the decarbonization of its energy matrices and to reduce their dependence on imported fuels. The use of vegetable oil for electricity generation has been explored mainly by Pacific Islands. Vanuatu island has two 4 MW diesel engines on Efate (the capital) running on a mixture of 30% coconut oil and 70% petroleum, 15% of the electricity generated comes from coconut oil [167]. The island of Tokelau declared in 2011 its intention to become the world's first 100% renewable country. This is to be achieved by a Photovoltaic mini-grid on each of the 3 islands that would provide 90% of the electricity demand with the remaining 10% to come from coconut oil. Samoa island also presents a small-scale coconut oil utilization by its power utility [168].

The feasibility of using waste cooking oil (WCO) as an alternative energy feedstock in islands has also been addressed in some researches as: Evaluating the potential of biodiesel (via recycled cooking oil) use in Singapore [169], feasibility for Langkawi WCO (waste cooking oil) derived-biodiesel [170].

Existing environmental impact studies of biofuels derived from oleaginous feedstocks have mainly focused on biodiesel such as life cycle analysis of biodiesel production [171], comparative life cycle assessment of diesel production from crude palm oil and waste cooking oil via pyrolysis [172], comparative life cycle assessment of alternative strategies for energy recovery from used cooking oil [173], substitutable biodiesel feedstocks for the UK [174], and used cooking oil-to-biodiesel chain in Europe [175].

Furthermore, some authors have studied the combustion emissions of trans-esterified WCO mainly in automotive sources as effects of the fuel injection pressure on the performance and emission of a diesel engine fueled with waste cooking oil biodiesel-diesel blends [176], butyl-biodiesel production from waste cooking oil; fuel properties and emission performance [177], among others.

As shown, although some research has been conducted about environmental impacts and emissions performance of oleaginous derived fuels, few authors have addressed these issues from the perspective of its straight use as fuel (non-trans esterified) in fixed sources for electricity production [178,179].

Besides, converting waste streams such as waste edible oil into valuable resources represents a three-win solution, dealing simultaneously with human security, pollution, and energy recovery [180].

2.2.1. Bioenergy and carbon neutrality

As in most islands, electricity generation in the Galapagos Islands is heavily based on fossil fuels. According to its energy balance, 89% of the electricity produced in the islands comes from fossil fuels, 8.2% from wind, 2.5% from solar, and 0.1% from biofuels [81].

Floreana Island is the smallest (172.29 km^2) of the inhabited islands of the Galápagos archipelago. It is located at 1,000 km from Continental Ecuador [181]. Since 2010, the biofuel pilot program has operated on the island using pure Jatropha curcas oil as an energy source in three dual electricity generators, which can work indistinctively with 100% diesel, 100% pure vegetable oil, or any proportion of blends among those. The thermoelectrical group produces 256,713 kWh per year [81]. The current electricity generation by source in Galapagos is shown in Table 9.

Table 9. Electricity generation by source in Galapagos

Island	Energy by Source (kWh)					Fuel Used Per Island (L)	
	Diesel	Wind	Solar	Jatropha	Total	Diesel	Jatropha Oil
San Cristobal	9,924,334	3,864,393	17,250		13,805,977	2,929,824	
Santa Cruz	27,732,054	38,267	1,194,922		28,965,243	7,532,996	
Isabela	4,411,835				4,411,835	1,340,016	
Floreana	208,015		3112	48,698	259,825	74,944	18,367
Total	**42,276,238**	**3,902,660**	**1,215,284**	**48,698**	**47,442,879**	**11,877,780**	**18,367**

Source: MEER (2015) [81])

The Biofuel program also seeks to reach other islands in the future. The estimation of biofuel demand for a B20 blend (20% biofuel- 80% diesel) for San Cristobal and Isabela islands is 585,964.4 and 268,003.2 litres of biofuel per year, respectively [29].

In terms of electricity generation, Floreana´s biofuel pilot project has tracked diesel and jatropha oil efficiency in terms of kWh produced per litre of fuel, which is 3.43 and 2.64, respectively [81]. Although pure Jatropha oil is the current sole biofuel source for electricity generation in Floreana, just 18.7% of the total electricity produced on the island because of the absence of a robust supply chain. Jatropha curcas production is exclusively based on the recollection of mature fruits from plants used as life fences in Manabí province located in the coastal region of continental Ecuador, the agricultural production of the plant at a commercial scale is inexistent in the country. Thus, it is essential to identify environmentally friendly alternatives to permit the permanence of the biofuel project in the islands. As seen in Table 1, the proportion between jatropha oil and diesel is 19.6% vs. 80.4%, respectively [182].

According to Noboa (2019) to progressively replace fossil-based energy in Ecuador, other types of non-conventional renewable technologies such as biomass (solid, liquid and gas), must be developed [183].

2.2.2. Galapagos Zero Fossil Fuel initiative

Galápagos has endured severe environmental, and economic impacts from fossil fuel spill on its marine reserve. The most serious caused by the spill from a tanker in 2001, in San Cristóbal Island. A total of 662,447 litres of diesel and fuel oil were spilt into the sea. This disaster triggered the decision to foster renewable energy implementation on the islands. In this context, the "The Zero Fossil Fuels" initiative was adopted [28]. One component of the mentioned project is the biofuel program that pursues to reduce the environmental footprint attributed to fossil fuel usage through its partial replacement with vegetable oils. Besides, risks associated with fossil fuel transportation from the mainland to the islands could also be addressed. The biodegradation time of oleaginous biofuels is 80.4 - 91.2% after 30 days, while fossil diesel reaches 24.5% biodegradation during the same period [184].

2.3. Circular economy and energy

Circular economy (CE) is an emerging alternative concept to a traditional linear economy (make, use, and dispose) in which resources are kept in use for as long as possible, extracting the maximum value from them whilst in use, and recover and regenerate products and materials at the end of each service life [185]. The use of waste flows as an energy source is complementary to CE principles [186].

2.4. Waste cooking oil as an alternative energy source

Waste cooking oil (WCO) is an oil-based substance that has been used in cooking or food preparation and is no longer suitable for human consumption [187]. Disposal of large amounts of WCO has become a problematic issue in most countries. WCO cannot be discharged into drains or sewers because this will lead to blockages and odour or vermin problems and may pollute watercourses causing problems for wildlife [188]. It is also a prohibited substance and will cause problems if dumped in municipal solid waste landfill and municipal sewage treatment plants [189]. When WCO reaches natural ecosystems, such as rivers, aquifers, or subsoil, the environmental consequences can be severe. In terms of economic and energy costs, the inappropriate disposition of used cooking represents: 3 kWh and about 1 €, respectively, per kg of WCO, delivered to the sewer system [190]. These risks must be highlighted in a fragile ecosystem as the Galapagos Islands.

Using WCO as an alternative fuel for energy generation could be a sustainable solution for disposal and greenhouse gases (GHG) abatement.

Many countries around the world e.g., Portugal, Greece, Italy, Spain, Belgium, Denmark, China, U.S.A, Australia, Germany, The U.K., and Korea, have implemented normative for using WCO with energy ends [191]. Also, WCO could be used as an in situ produced biofuel to reduce environmental and capital costs in line with circular economy principles.

The use of this potential energy source would also reduce in a significant manner the environmental impact of fossil fuel-based energy generation in islands. In this context, collecting and recycling WCO contributes to solving simultaneously three environmental problems: waste reduction by reuse/recovery, reduction of fossil fuels dependence, and reduction of pollutant emissions [192]. Furthermore, studies developed by (Caldeira et al., 2018) [193] show advantages regarding water footprint for WCO when compared with other biodiesel feedstocks finding the lowest impact for WCO with 0.03 world m^3eq/kg, while for Palm oil, the results show 1.26 world m^3eq/kg.

According to Capuano et al. [178], the use of WCO in diesel engines is much more feasible for a stationary generation of electrical and thermal energy, an illustrative example is the Vegawatt system developed by Owl Power Company in the U.S.A. which produces electricity in situ using WCO [194], and in low-speed diesel engines, i.e. those of large ships [195], than for automotive applications. In this last case, direct use of WCO on a large scale is currently not feasible due to the need of changes in the design of the engines, as well as for the organization of the distribution network. Physical and chemical properties comparison of Palm oil, WVO, and diesel are shown in Table 10.

The use of WCO in the context of the present study complies with the three principles of Circular economy: i) Design out waste and pollution, ii) Keep products and materials in use and iii) Regenerate natural systems [185].

Table 10. Physical and chemical properties comparison of Palm oil, Waste cooking oil (WVO) and diesel

Properties	Palm oil	WVO	Diesel
Viscosity (eSt) (40 °C)	39-43	31-50	2.5-4.5
Density (15 °C) (kg/m3)	860-920	910-943	820-860
Heating Value (MJ/kg)	36.5-40.1	32.2-41.8	43.0-46.0
Cetane number	42-49	36-37	45-56
Flash point (40 °C)	267-304	>250	>52.0
Iodine Value	35-66	98-128	-
Sources	[196] [154] [197] [198] [199]	[200] [201] [202] [203] [204] [205] [206]	[207] [208] [189] [201]

Diesel consumption for electricity generation in CARICOM's islands is 218 million liters per year or 8,4 M GJ [12]. Taking into account the annual vegetable oil consumption of the Caribbean region [25], the recovery ratio determined by Sheinbaum et al 2013 [209], and the urban population in each island. It is estimated a hypothetical availability of 124 million litres per year of regenerated WCO or 4,2 GJ which could be used with energy ends to replace 44% of diesel imports.

3. Materials and Methods

In this chapter, the materials used, and the methodology applied to the experimental phase of the thesis is described. Following the established objectives, two main research topics were addressed to identify promising second-generation bioenergy resources in Ecuador. The first topic, regarding a Life Cycle Assessment of electricity feedstocks, studied for Galapagos Islands, and second, the agro-ecological zoning and energy potential estimation of dedicated energy crops in continental Ecuador.

3.1. Life Cycle Assessment of Bioenergy in Islands

3.1.1. Life Cycle Assessment

Life Cycle Assessment (LCA) is a quantitative methodological framework to assess the environmental performance of products and services throughout their life cycle. LCA has been used with success to assess the environmental sustainability of bioenergy systems [86,210–212].

3.1.2. LCA Impact evaluation methodology

The Life Cycle Impact Assessment (LCIA) method used in this part of the study is the CML 2001 (baseline) methodology [83]. This methodology uses the damage-oriented approach or endpoint approach for impact assessment. Impact categories considered in this methodology include the following: carcinogens, respiratory organics and inorganics, climate change, ionizing radiation, ozone layer depletion, ecotoxicity, acidification/eutrophication, land use, minerals and fossil fuels uses.

3.1.3. Software

Software Simapro version 9.0.033 was used to calculate the impacts determined by the mentioned method. A contribution analysis was performed to understand the contributions of specific processes and pollutants to the total impact scores per impact category, and to find the reasons for the changes of environmental impacts between RPO and WCO.

Processes and materials were obtained from in situ research and Ecoinvent database [213].

3.1.4. Functional Unit

The final functional unit (FU) of this study was defined as 1 MWh produced on Floreana Island.

3.1.5. Life Cycle inventory

The Inventory analysis was developed according to ISO 14040 standards [82], and includes the required energy and materials (inputs) flows as well as products, co-products, emissions and wastes (outputs) emitted to the environment during all the considered processes.

3.1.6. System boundary and data sources

3.1.6.1. Refined palm oil

Electricity generation from palm oil in islands have mainly being focused in its byproducts [214–216]. In this regard, this study aims to explore the environmental impacts related to the direct use of refined palm oil (RPO) as electricity feedstock in islands. Latin American region exports 1.9 million tons of palm oil per year [217]. In Ecuador, the crop contributes 4% of the agricultural gross domestic product (GDP). The production of this commodity presented an annual growth of 8%, from 2010 to 2016, becoming the seventh agricultural export and one of the most dynamic industries of the country. In the last 5 years, 42% of palm oil produced in Ecuador was consumed internally while 58% was exported for a total of 271,000,000 USD. Ecuador is the seventh palm oil exporter worldwide. Palm oil production in Ecuador accounts with 300,000 hectares with a total investment of 2,2 billion USD and generates 127,000 jobs [21].

According to the Palm Oil Producers Association of Ecuador (FEDEPAL, by its acronyms in Spanish), 78,737 tons the equivalent to 70,154,667 litres were exported in 2018 [22]. This number shows that the potential biofuel demand for Galapagos Islands could be easily satisfied only by palm oil.

The selection of the agricultural area for this case study was supported by the Palm Oil Improvement Unit of the National Institute of Agricultural Research of Ecuador (INIAP, by its acronyms in Spanish). The selected study area is located on latitude: 0°11'22.79"S, longitude: 79°12'8.62"W and represents the typical palm oil agricultural systems of Esmeraldas province, one of the largest producers in Ecuador. The following stages described in Figure 6 were addressed: i) oil palm plantation, ii) palm oil production, iii) crude palm oil extraction, iv) palm oil refining (Manabí province), and v) electricity generation (Floreana Island). Transportation at all stages was included.

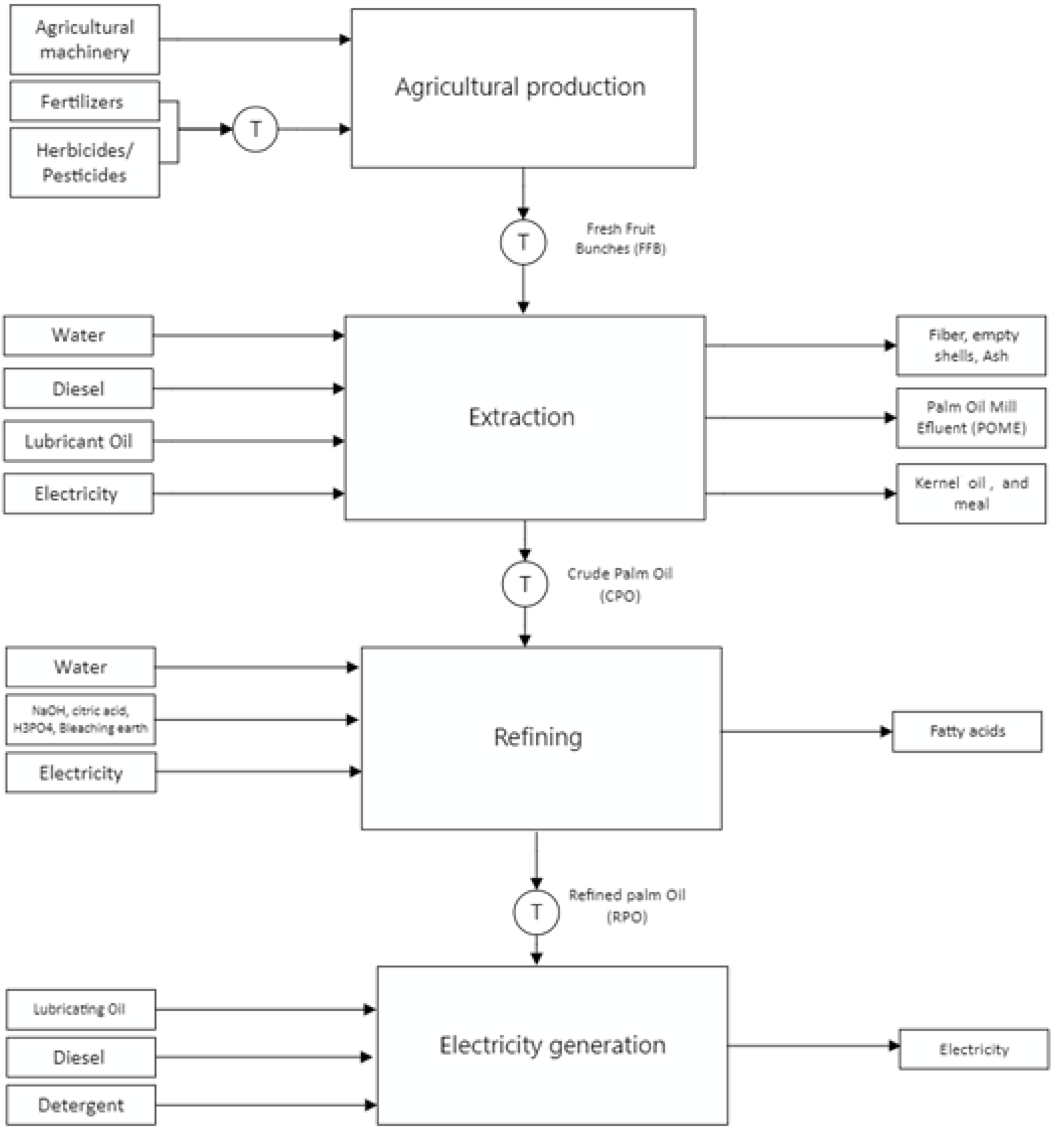

Figure 6. Refined palm oil electricity-based system boundaries

Agricultural phase inventory.

The input data of materials and energy to produce 1 ton of palm oil fresh fruit bunches (FFB) (unit output in this phase) was addressed. The cultivation stage includes all the agricultural activities dedicated to the production of immature/mature plants. The data collected was the result of in situ visits and experts’ criteria. The yield was defined as an average obtained in field research and statistics developed by INIAP [218]. Regarding land-use change, although palm oil cultivation is linked to deforestation mainly in the Amazonian region of Ecuador [219], the selected productive zone does not present this pattern because has been under production for 60 years, while the studied crops have an average age of 12 years. Therefore, no land-use changes were attributed in this study.

It must be mentioned that the selected plantations have a better production yield when compared to the national average due to the application of best agricultural practices recommended by the research centre [218]. Information regarding the land-use change, fertilizers, pesticides, herbicides, machinery use, and inputs transportation was collected during visits.

The average agricultural conditions of productive units studied are shown in Table 11.

Table 11. Palm oil plantation studied characteristics

Characteristic	Number
FFB yield (t/ha year)	18
Plant density (ha)	142
Plantation lifetime (years)	25
Total area (ha)	2,800

Source: In situ surveys

Average yearly yields, as well as inventory data of fertilizers, herbicides, pesticides, and energy usage during plantation and harvesting, were collected in situ. Adjustments were made using recommendation charts developed by INIAP [218].

Fertilizers. The total amount of applied fertilizers in the studied plantations was calculated for 25 years as the productive period of the crop. Manure based fertilization in palm oil crop is not a common practice in Ecuador, hence it was not included in the study.

Herbicides, pesticides. Data for herbicides and pesticide used per FFB ton produced in Ecuador were compiled during site visits, adjustments were made by INIAP.

Energy. In terms of energy consumption, one source was identified: gasoline used on agricultural machinery (motorized bush cutter).

Transport. The transportation of agricultural inputs from the warehouse to the plantation in EURO 1, 10-ton capacity trucks was included using ton-kilometre (tkm) units.

Emissions at the agricultural phase.

The emissions outputs analyzed in this part of the study were: emissions to air, water and soil, occurred during the agricultural production of 1 FFB ton.

Emissions derived from the use of fertilizers were determined using methodologies and models developed by: IPCC (2006) [220], Schmidt et al. (2007) [221], Asman (1992) [222], Audsley et al. (1997) [223], and Canals (2003) [224]. Pest LCI2.0.8 model was used for determining pesticides emissions to soil, air and water [225]. Heavy metals emissions were calculated using the models and methodologies developed by Nemecek et al (2001) [226], Oberholzer et al. (2011) [227], and Prasuhn (2006) [228]. Emissions from fertilizers production and pesticides used in the plantation were determined by the Ecoinvent database. Inputs were assigned for 1 ton of FFB (Table 12). Finally, the values were processed in Simpapro 9.0.0.3 software considering its origination and end: nature or technosphere.

Table 12. Inputs and outputs in the agricultural production of 1 FFB ton

Inputs/Outputs	Unit	Amount
Inputs		
Urea	kg	7.6
Ammonium sulphate	kg	1.4
Triple superphosphate	kg	9.5×10^{-1}
Di ammonium phosphate	kg	2.2×10^{-1}
Potassium sulphate	kg	3.0×10^{-2}
NPK (15–15–15) compound	kg	5.2
Potassium chloride	kg	1.4×10^{1}
Transport	tkm	8.2
CO_2	kg	1.1×10^{3}
Glyphosate	kg	4.1×10^{-1}
Metsulfuron	kg	6.9×10^{-1}
Benfuracarb	kg	6.1×10^{-2}
Gasoline	l	2.0×10^{-1}
Output		
Carbon dioxide (air)	kg	1.0×10
Ammonia (air)	kg	7.6×10
Nitrate (air)	kg	1.3
Dinitrogen monoxide (air)	kg	8.5×10^{-2}
Nitrogen monoxide (air)	kg	8.5×10^{-3}
Glyphosate (air)	kg	1.4×10^{-2}
Metsulfuron-methyl (air)	kg	2.3×10^{-3}
Nitrate (groundwater)	kg	1.3
Cadmium (groundwater)	mg	3.8×10^{-1}
Copper (groundwater)	mg	2.3×10
Zinc (groundwater)	mg	4.4×10
Lead (groundwater)	mg	2.0×10^{-1}
Chromium (groundwater)	mg	1.7×10^{2}
Phosphate (river)	kg	8.3×10^{-3}
Glyphosate (river)	kg	3.2×10^{-4}
Metsulfuron-methyl (river)	kg	8.1×10^{6}
Glyphosate (groundwater)	kg	4.4×10^{-2}
Metsulfuron-methyl (groundwater)	kg	5.3×10^{-3}
Glyphosate (soil)	kg	5.9×10^{-1}
Metsulfuron (soil)	kg	5.9×10^{-1}
Cadmium (soil)	mg	6.8
Copper (soil)	mg	4.8×10^{2}
Zinc (soil)	mg	2.5×10^{2}
Lead (soil)	mg	2.5×10
Chromium (soil)	mg	7.5×10^{2}
Nickel (soil)	mg	1.4×10^{2}
FFB	t	1

Industrial phase inventory.

In the extraction process the palm oil mill type studied is located in Esmeraldas province; latitude: 0° 1'34.25"N, longitude: 79°23'54.65"W. The facility has a processing capacity of 5.6 tons of FFB per hour (90 tons of FFB per day). The distance from the plantation to the facility is 31.5 km by road. Process data were obtained from monthly reports provided by the management department. The average crude palm oil (CPO) yield in the studied oil mill is 0.185 ton per ton of FFB processed. Fibre residues, 150 kg per ton processed, are used as fuel for generating steam that supplies 97.6% of the total energy demand of the plant, the rest is purchased from the grid, nevertheless, a diesel-based electricity generator is used in case of electricity shortage and to start engines. The economic allocation was selected in the extraction phase. Table 12 presents the inputs used in this production phase.

In the refining process, the CPO extracted is transported to a refinery facility located at 258 km from the oil mill by road. The refining process removes odours, flavours, and impurities trough bleaching and deodorizing methods. The mass balance of the studied system resulted in a yield of 1ton of RPO per 1.08 ton of CPO. Inputs and outputs for this phase are shown in Table 13.

EMISSIONS AT THE INDUSTRIAL PHASE

Emissions to water were estimated form the methodology developed by Wahid et al (2015) [229], and emissions to air from Jungbluth et al. (2007) [230].

Emissions to water and air due to the use of the national electricity grid of Ecuador were adapted from Ramirez et al. (2019) [231] using the electricity mix of the year 2018.

Table 13. Inputs and outputs for the extraction of 1 ton of crude palm oil

Inputs/Outputs	Unit	Amount
Input		
Water	t	5.4
FFB	t	5.1
Lubricating oil	kg	2.7×10^{-3}
Energy, from diesel	kWh	1.4
Transport, truck	tkm	3.1 × 10
Electricity, grid continental (Ecuador)	kWh	1.4
Electricity, co-generation biomass	kWh	1.3×10^{2}
Heat and power co-generation unit, building construction	p	4.4×10^{-6}
Heat and power co-generation unit, components	p	1.7×10^{-5}
Heat and power co-generation unit, component construction	p	$1.7 \times 1^{0-5}$
Output		
Carbon dioxide, biogenic (air)	kg	3.2
Methane (air)	kg	1.5 × 10
Nitrogen oxides (air)	kg	2.0
Particulates, <2.5 um (air)	kg	1.0
Carbon monoxide, biogenic (air)	kg	1.5 × 10
Methane, biogenic (air)	kg	9.8×10^{-3}
Non-methane volatile organic compounds (NMVOC) (air)	kg	1.3×10^{-2}
Sulfur dioxide (air)	kg	5.6×10^{-2}
Dinitrogen monoxide (air)	kg	5.1×10^{-2}
Acetaldehyde (air)	kg	1.3×10^{-3}
Hydrocarbons, aliphatic, alkanes, unspecified (air)	kg	2.0×10^{-2}
Hydrocarbons, aliphatic, unsaturated (air)	kg	7.0×10^{-2}
Arsenic (air)	kg	2.2×10^{-5}
Benzopyrene, methyl (air)	kg	1.1×10^{-5}
Benzene (air)	kg	2.0×10^{-2}
Bromine (air)	kg	1.3×10^{-3}
Calcium (air)	kg	1.3 × 10
Cadmium (air)	kg	1.5×10^{-5}
Chlorine (air)	kg	4.0×10^{-3}
Chromium IV (air)	kg	9.0×10^{-7}
Copper (air)	kg	4.9×10^{-4}
Dioxin (air)	kg	7.0×10^{-10}
Ethyl benzoate (air)	kg	6.7×10^{-4}
Fluoride (air)	kg	1.1×10^{-3}
Formaldehyde (air)	kg	2.9×10^{-3}
Benzene, hexachloride (air)	kg	1.6×10^{-10}
Mercury (air)	kg	5.9×10^{-8}
Potassium (air)	kg	5.3×10^{-1}
Magnesium (air)	kg	3.8×10^{-3}
Manganese (air)	kg	3.4×10^{-5}
Sodium (air)	kg	2.9×10^{-2}

Inputs/Outputs	Unit	Amount
Ammonia (air)	kg	3.9×10^{-2}
Nickel (air)	kg	1.3×10^{-4}
Phosphorus (air)	kg	6.7×10^{-3}
Polycyclic aromatic hydrocarbons (air)	kg	2.4×10^{-4}
Lead (air)	kg	5.6×10^{-4}
Phenol, pentachloro- (air)	kg	1.8×10^{-7}
Toluene (air)	kg	6.7×10^{-3}
m-Xylene (air)	kg	2.7×10^{-3}
Zinc (air)	kg	6.7×10^{-3}
Chromium (air)	kg	9.0×10^{-5}
Nitrogen, total (to freshwater)	t	1.0×10^{-2}
Oils, biogenic (to freshwater)	t	6.1×10^{-2}
BOD, biological oxygen demand (to freshwater)	t	3.1×10^{-1}
COD, chemical oxygen demand (to freshwater)	kg	6.7×10^{-1}
Crude palm oil	t	1

Table 14. Inputs and outputs for producing 1 ton of refined palm oil

Inputs/Outputs	Unit	Amount
Input		
Water	L	1.5×10^{2}
CPO	kg	1.0×10^{3}
Bleaching earth	kg	8.0
Phosphoric acid	kg	9.6×10^{-1}
Citric acid	kg	7.7×10^{-1}
Sodium hydroxide	kg	3.4×10^{-1}
Electricity EC grid	kWh	1.6×10
Transport, truck < 10 t, EURO1	tkm	2.1×10^{2}
Output		
RPO	t	1
Fatty acids	kg	7.0×10
Water vapor	m^3	6.3×10
Wastewater from vegetable oil refinery	m^3	8.7×10

Ground transportation.

The palm oil processing mill studied is located 31.5 km from the plantation in Esmeraldas province, while the refining plant is in Manabí province at 258 km. Once the oil is extracted, it is transported by a 10-ton capacity truck to Timsa port in Guayaquil city. The distance between the processing plant and the port is 326 km by road. Ton-kilometer (tkm) units are included in the study for each transportation stage.

Assuming the full capacity of a 10-ton truck, the total amount of 3,260 tkm was estimated. For one metric ton of pure palm oil, it was assigned 326 tkm for road transportation to Timsa port in Guayaquil city. Finally, once the RPO arrives at Floreana Island it is transported 0.5 km by truck to the electricity generation facility. The means of transportation selected from Ecoinvent database in this phase was Transport, truck <10t, EURO 1.

Marine transportation

Once the refined palm oil arrives at Timsa port in Guayaquil city, it is shipped to Floreana Island in Galapagos. The route is made by an 834.5-ton capacity tanker ship. The route comprises 1,283 km to Velasco Ibarra port in Floreana island. Assuming the vessel is travelling at full capacity, the allocation results in 1,283 tkm for the unit output of 1 Tm of RPO (4,119 litres). For this component, a 960-ton capacity barge ship container with, 80% LF, the empty return was selected from the Ecoinvent database.

Electricity generation

In Floreana island, three 89 kW, DEUTZ generators model BF4M101E, the year 2010, has been adapted to work with diesel and vegetable oil or any blend between those. The fuel currently used is a blend of diesel and pure jatropha oil which varies in proportions according to the availability of the latter. According to Galapagos energy balance, on average 9.83 kWh are generated per gallon of vegetable oil [81]. According to the reference information provided by Galapagos energy balance, it was calculated that 385,086 liters of RPO or 353.085 kg must be used to generate 1 MWh. The inputs and outputs of this phase are included in Table 15.

Table 15. Inputs and outputs to produce 1 MWh from refined palm oil

Inputs/Outputs	**Unit**	**Amount**
Input		
RPO	kg	3.5×10^{2}
Lubricating oil	kg	1.9
Transport, truck < 10 t EURO1	tkm	1.4×10^{2}
Marine transport 350 t ship	tkm	4.2×10^{2}
Heat and power co-generation unit, 50 kW electrical, components	p	7.7×10^{-4}
Sodium hypochlorite	kg	$1.1x \times 10^{-5}$
Water	kg	1.8×10^{2}
Output		
Carbon monoxide, biogenic	kg	2.3×10
Carbon dioxide, biogenic	kg	4.8×10^{2}
Hydrocarbons	kg	8.6×10
Electricity	MWh	1

3.1.6.2. Waste vegetable oil

The current population of Galapagos islands is 25,500 people [40]. In addition, according to the annual Visitor Report to the protected areas of Galapagos [232], an average of 228,306 tourists (floating population) visit the archipelago every year with average permanency of 7 days, 77% of the total; 159,814 tourists, stay in Santa Cruz island.

On the other hand, the average edible cooking oil consumption per capita in the Latin American region is 20 kg [233]. The food´s oil absorption ratio is 25% [234]. Nevertheless, a real WCO recovery ratio in the region is estimated from 20% to 45% [209] [235]. In this regard, it can be determined an average WCO potential recovery between 114,259.70 and 257,084.33 kg, or between 121,287.99 and 272,898 litres per year in Santa Cruz island.

According to Galapagos energy balance, Floreana island uses per year 74,944 litres of diesel and 18,367 litres of vegetable oil (Jatropha curcas) as fuels in its dual electricity generators [81]. In this regard, the fuel demand can be easily covered by WCO produced in Santa Cruz island.

In addition, the implementation of a WCO value chain could develop a new local industry, creating local employment and reducing foreign exchange expenditures on energy.

WCO in situ production inventory.

In this section of the study, a hypothetical WCO production system was studied in Santa Cruz island, its boundaries (Figure 7) include: i) washing containers, ii) WCO collection and transportation to the processing plant, iii) delivering of WCO from collection point to the plant, iv) pre-treatment, v) processing at the cleaning facility, and v) transportation to Cogeneration plant. Unit output: In this phase, 1 metric ton of recovered WCO is used as unit output.

It must be mentioned that WCO is assumed to be a waste. Therefore, the agricultural and industrial production phases are not included, according to standard procedure for the life cycle of waste [236,237].

WCO collection.

A hypothetical WCO collection system (Figure 8) was drawn in Santa Cruz island, the largest populated and the main touristic destination of Galapagos. 120 potential WCO collection sites were identified through in situ visits: 32 restaurants and 88 hotels.

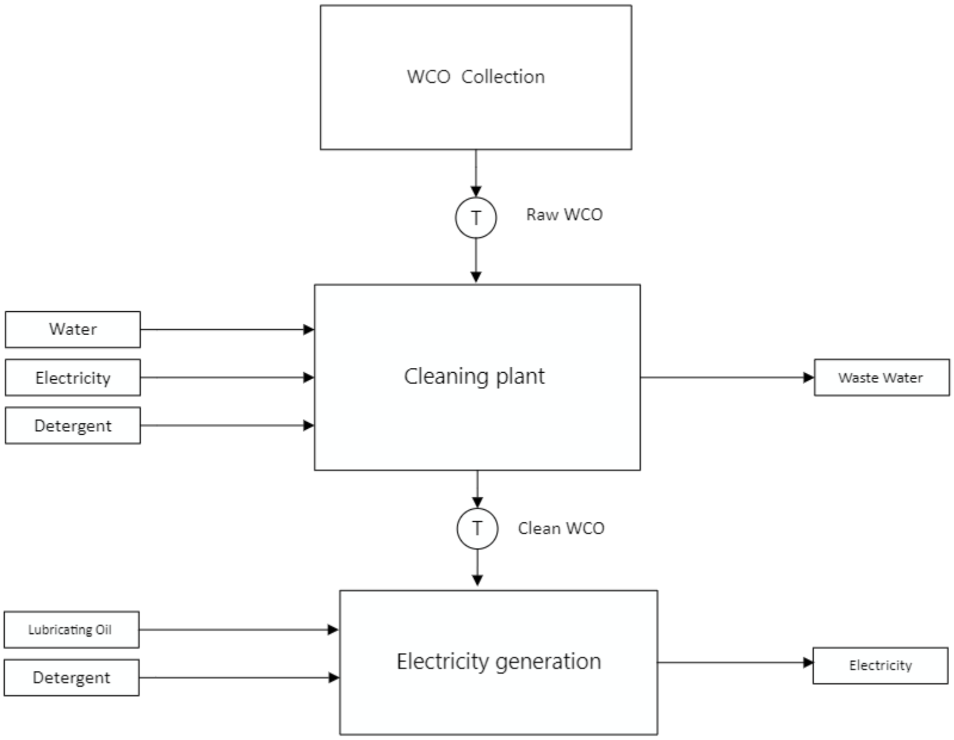

Figure 7. WCO Electricity based System boundaries

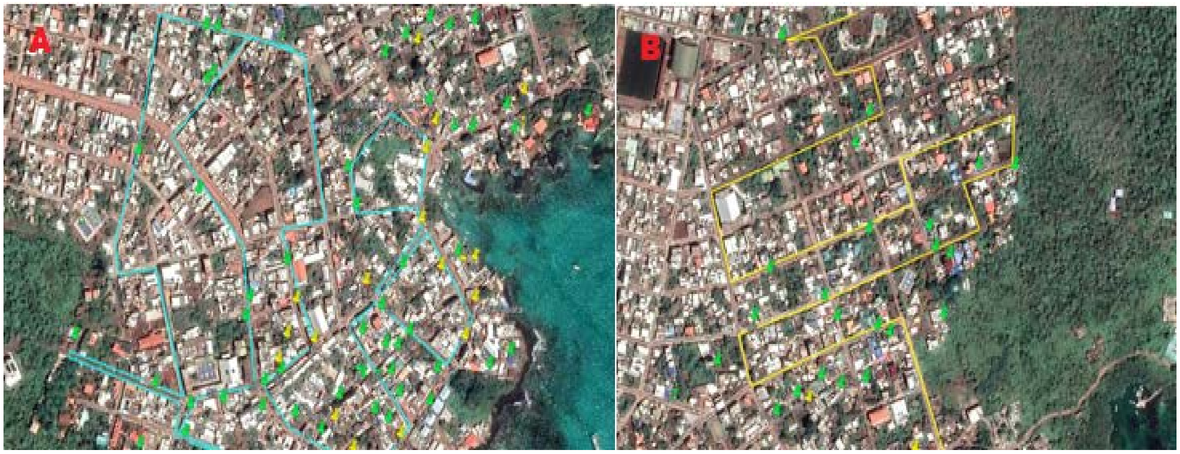

Figure 8. Collection circuits drafted in Santa Cruz Island: A, South circuit; B, North Circuit

Source: Author, satelital images Google Earth Pro

Two collection routes were drawn. The first in the southeast zone of the island with 4.47 km and the second in the northeast zone of the island with 3.72 km, in total 8.7 km. Both collecting routes end in a hypothetical cleaning facility located in the electricity company facilities in the following coordinates: latitude 0°44'37.81''S, longitude 90°19'11.97''W.

WCO cleaning.

The WCO processing phase comprises the following activities: i) washing containers, ii) oil regeneration, iii) pre-heating, iv) decantation, v) sieving and pumping, and vi) extraction/filtration. The use of electricity and water were estimated according to Lombardi et al. (2018) [173].

Materials and infrastructure were estimated according to Ripa et al. (2014) [180]. Table 16 shows the inputs required to produce 1 metric ton of regenerated waste cooking oil.

The electricity mix in Santa Cruz island was modelled in Simapro according to the technologies reported in the energy balance of Galapagos islands. [81].

Table 16. Inputs and outputs to produce 1MWh from waste cooking oil

Inputs/Outputs	Unit	Amount
Input		
Water	L	9.8
Transport, truck < 10 t	tkm	8.0
Electricity grid Galápagos	kWh	4.6×10
Steel, low-alloyed steel production	p	6.4×10^{-2}
Pump, 40 W production	p	2.2×10^{-2}
Sodium hypochlorite	kg	1.1×10^{-5}
Output		
Wastewater	L	1.2×10^{2}
Clean WCO	t	1

Transport.

For the recollection phase, it is assumed the use of a EURO1, 10-ton capacity diesel truck, from the Ecoinvent database, and 8.7 tkm were assigned. The treated WCO is transported seaway from Santa Cruz Port 56.49 km to Simon Bolivar port in Floreana island. The transport system to be used in this stage is a cargo catamaran. Assuming that the vessel is travelling at full capacity, it was assigned 56.49 tkm for the unit output of 1 Tm of pure palm oil (1,088 litres). For this component of the process, a barge ship, container, 960t, 80% LF, empty return / GLO Economic was selected from Ecoinvent database.

Electricity generation.

The electricity production process was described above. Inputs and outputs in this phase are detailed in Table 17.

Table 17. Inputs and outputs to produce 1 MWh from waste cooking oil

Inputs/Outputs	Unit	Amount
Input		
Lubricating oil	kg	1.9×10
Transport, truck < 10 t, EURO1	tkm	3
Marine transport 350 t ship	tkm	1.9×10
Heat and power co-generation unit, 50 kW electrical, components	p	7.7×10^{-4}
Sodium hypochlorite	kg	1.1×10^{-5}
Water	kg	1.8×10^{2}
WCO	kg	3.5×10^{2}
Output		
Carbon monoxide, biogenic	kg	1.3×10
Carbon dioxide, biogenic	kg	4.9×10^{2}
Hydrocarbons	kg	8.6×10
Electricity	MWh	1

3.1.7. Emission measurement in electricity generation

For this phase of the study, an emissions test was carried out in similar conditions to Floreana island using RPO and WCO. Emission gas analyzer TESTO 350, was used for determining the following parameters: Carbon dioxide, carbon monoxide, and hydrocarbons [238].

One metric ton of RPO was purchased from a local provider and the same amount of WCO: 20% collected from 5 different locations and 70% purchased from a local cooking oil recycler. WCO was decanted and filtered in a press filter Figure 9. It must be mentioned that the recycling company exports 100,000 litters of WCO monthly to the European Union where it is converted to biodiesel [26].

Figure 9. A, WCO reception in containers; B, WCO filtration; C, Emission test

The emission test was carried out in Quito city in a test system provided by the Institute of Geological and Energy Research of Ecuador (IIGE, by its acronyms in Spanish). The test system consists of a diesel direct injection, horizontal, single-cylinder, four-stroke engine brand YANMAR type NFD 13, adapted to an electricity generator. An emission sampler was installed by the end of the exhaust pipe where the emission sampling probe TESTO 350 was set. A combustion emission measurement trial was performed for each of the fuel batches. To estimate the use of the cogeneration unit, an average of electricity production for 15 years of life expectancy was estimated from the Ecoinvent database.

3.2. Agroecological Zoning of second-generation energy crops

3.2.1. Agroecological Zoning Methodology

The Food and Agriculture Organization of the United Nations (FAO), jointly with the International Institute for Applied Systems Analysis (IIASA), developed the Agroecological Zones (AEZ) methodology [84]. This methodology enables an evaluation of biophysical limitations and the production potential of major agricultural commodities. AEZ can be defined as the process of identifying areas with exclusive characteristics, which differentiate them from others; its characterization concerning physical (climate, soil, landforms), biological (vegetation, fauna,) and its evaluation about the aptitude for sustained use for some Land Use Types (LUT). Agroecological zoning consists in the identification of areas with similar agroecological characteristics taking into account the edaphic (texture, depth, precipitation, stony, drainage, salinity, pH, fertility, slope) and climatic requirements (Temperature, precipitation) of a determined crop and the conditions given by an ecosystem. This information merge results obtaining limitations and potentials for the development of a specified crop. The agro-ecological zones are defined as homogenous and contiguous areas with similar soil, land, and climate characteristics.

The resulting LUT can be defined at different levels of generalization or, at the level of specific crops, depending on the purpose of zoning and the information available [84].

For the ZAE methodology to be used for different purposes related to the use of land resources, some modifications are required. Among these, the definition of the most complex LUT determines the need for alternative procedures for estimating potential productivity and the climatic and soil requirements to be used in evaluating the feasibility of the use of agro-ecological cells. It must also provide the elements required to determine the economic viability and social acceptability of LUTs identified as physically viable. It should also contemplate the need to consider the current land use and the need to reserve preservation areas in cases of particularly fragile ecosystems, such as those with soils whose degradation is anticipated in case of submitting to new management systems. Likewise, it must consider the need for recreation areas and refuge areas for fauna and flora and the preservation of genetic diversity of plants or animals, to avoid irrecoverable losses of biodiversity. Socioeconomic factors, necessary for land use planning and economic viability analysis of the proposed LUTs, can be included in varying degrees of aggregation and level of detail of the presence of man and his social and economic activities [85].

3.2.2. Development of the structured query language

This agrological model is a mathematical function in which, from the structured language of consultation to the agroecological map attributes, within a GIS, the optimal zones are generated, which have the best natural edaphological and climatic conditions for the development of the studied crops. This model permits better control when defining the areas since it limits the selection based on the requirements of the crop to be zoned [90].

3.2.3. Software

QGIS is an open-sourced software suite consisting of a group of geographic information system (GIS) software products. It is used for creating and using maps, compiling geographic data; analysing mapped information; sharing and discovering geographic information, using maps and geographic information in a range of applications, and managing geographic information in a database. The software is available to run in WMS 1.3, WFS 1.0.0, WFS 1.1.0, OGC API for Features 1.0 (WFS3), and WCS 1.1.1, which implements cartographic features for thematic mapping. QGIS server is a FastCGI/CGI (Common Gateway Interface) application written in C++ coding language that works with a web server [239].

3.2.4. GIS maps characteristics

Cartographic parameters of maps used in this study are:

- Scale 1:25,000.
- Cartographic Projection Universal Transversal de Mercator.
- Cartographic zone 17 South.
- Format Shape (.shp), Geodatabase Personal.
- Half Vertical datum Half sea level.
- Horizontal Datum World Geodetic System 1984.

Maps used:

- Edaphic (pH, salinity, slope, deep, texture, drainage).
- Land Use.

- Protected areas.
- Isotherms.
- Isohyets.

3.2.5. Crop selection

A bibliographical review was performed to identify potential bioenergy crops for electricity production adaptable to agroclimatic conditions of Ecuador. Mehmood et al. [240] identified 15 dedicated energy cultivars suitable to grow in marginal lands.

A prioritization was conducted within the preidentified crops considering the following desirable attributes: adaptable to tropical and subtropical climates, low moisture content, and have above a specific energy yield GJ/ha (year). Direct combustion is feasible only for biomass with a moisture content of less than 50%. High moisture content biomass is better suited to biological conversion processes [241]. Thus, high moisture content crops that are more suitable for biofuel production rather than direct combustion for electricity production were not included. [242–244]

The average yield for woody (Table 18) and nonwoody (Table 19) biomass crops was 209 GJ/ha·year and 239 GJ/ha·year, respectively. The selected crops were the ones presenting a higher bioenergy yield per hectare per year than the average.

Two additional crops were included in the study due to their high yields and adaptability to marginal lands, pine, and hemp. Pine was introduced as a woody crop in Ecuador in 1925 [245], currently accounts for 60,201.39 ha. Its primary use is for timber products; the crop has also being used in many countries as an energy feedstock [246,247]. Hemp was included because of its high energy yield [248,249], and its adaptability to marginal soils

[250,251]. The selected crops are Miscanthus, Eucalyptus, Giant reed, Pine, Hemp, and Bamboo.

Table 18. Non-woody biomass crops suitable for marginal lands

Crop	Suitable for Tropical and Subtropical climate	Low moisture content	Yield (t/ha/year) DM	Gross CV (MJ/kg) DB	Gross Energy potential (GJ/ha·year)	Source
Miscanthus *(Miscanthus spp.)*	x	x	16.20	17.49	283.34	[252]
Switchgrass (*Panicum virgatum L.*)	x	x	10.20	18.00	183.60	[252] [253]
Reed canarygrass *(Phalaris arundinacea L.)*		x	5.50	17.83	98.06	[254]
Virginia mallow *(Sida hermaphrodita)*		x	12.15	16.10	195.59	[255]
Cardoon *(Cynara cardunculus)*			13.50	15.00	202.50	[256]
Siberian Elm, *(Ulmus pumila L.)*		x	9.80	19.65	192.57	[257]
Tall Wheatgrass *(Thino pyrumponticum)*		x	13.00	15.79	205.27	[258]
Bamboo *(Bamboosa balcooa)*	x	x	21.00	19.40	407.40	[259]
Hemp *(Cannabis Sativa)*	x	x	13.00	18.80	244.4	[251] [249] [249]
Giant reed *(Arundo donax L.)*	x	x	25.00	16.89	422.25	[260]
Cup plant *(Silphium perfoliatum L.)*			6.70	17.19	115.17	[261]

Table 19. Woody biomass crops suitable for marginal lands

Crop	Suitable for Tropical and Subtropical climate	Low moisture content	Yield (t/ha/year) DM	Gross CV (MJ/kg) DB	Gross Energy potential (GJ/ha·year)	Source
Eucalyptus *(Eucalyptus globulus)*	x	x	22.00	18.00	396.00	[262] [263]
Poplar *(Populus tremula)*		x	4.30	19.13	82.27	[264]
Willow *(Salix spp.)*		x	7.80	19.33	150.77	[265]
Pine *(Pinus patula)*	x	x	17.10	19.30	330.03	[246] [266]

3.2.6. Crops description

3.2.6.1. Bamboo

Figure 10. Bamboo production field

Bamboo, *Bambusa Balcoa,* family Bambusoideae, is a native crop from Northeastern India cultivated in the villages of different states of this country [267]. The dull green culms of this species are 12–23 m tall, with 18–25 cm circumference and widely scattered up to an altitude of about 600 m [268]. Because of the accelerated growth pattern with a short developmental phase, bamboo attains an important position in cooperative agroforestry programs. Bamboo proves to be effective for CO_2 removal to control soil erosion [269].

3.2.6.2. Hemp

Figure 11. Hemp cultivation

Hemp, *Cannabis sativa L.*, family Cannabaceae, is one of the oldest crops globally, traditionally grown for its long bast fibre. Additionally, cannabinoids from hemp seeds have been used for medicinal, spiritual, and recreational purposes [270].

Hemp has lost its importance as a raw material for cordage and textile materials, being replaced by cotton and synthetic fibers [271]. It has been demonstrated that hemp can produce high annual yields of biomass from 13 to 17.5 t/ha per year [244, 246].

Furthermore, advantages over other energy crops are also found outside the energy balance, e.g., low pesticide requirements and weed competition. Future improvements of hemp biomass and energy yields may strengthen its competitive position against maize and sugar beet for biogas production and perennial energy crops for solid biofuel production [272].

3.2.6.3. Eucalyptus

Figure 12. Eucalyptus Cultivation

Eucalyptus, *Eucalyptus globulus,* family Myrtaceous, is a prime candidate for woody biomass plantations. It grows rapidly, reputedly accumulating 40 metric tons dry matter per hectare per year a wide range of sites in tropical locations. The material harvested is mostly herbaceous, with only 24% to 33% dry weight. Eucalyptus trees are relatively deeply rooted and could obtain water and nutrients below depths reached by most herbaceous perennial crops [263].

3.2.6.4. Giant Reed

Figure 13. Giant Reed Cultivation

Giant reed, *Arundo donax,* family Poaceae, grows abundantly with and presents a high yield capacity [273]. Research carried out on giant reed has highlighted the high productive potential in several subtropical climates [260]. This C3 plant has been studied as a potential carbon sink in European wetlands with promising results [274].

3.2.6.5. Pine

Figure 14. Pinus cultivation

Pine, *Pinus Patula*, family Pinaceae, is the most used species in forestry plantations due to the high cultivation yield that ranges from 12 to 22 m^3 per hectare per year [245]. The residues produced during pine processing are an interesting alternative for obtaining added-value products. Other advantages of pine in reforestation programs are related to its multiple applications and the no intensive silviculture practices [247].

3.2.6.6. Miscanthus

Figure 15. Miscanthus Cultivation

Miscanthus, *Miscanthus spp*., family Poaceae, is a C4 herbaceous plant originated in Asia perennial, rhizomatous grasses with lignified stems; once the plants are established, Miscanthus has the potential for very high rates of growth, growing stems larger than 3 m within a single growing season [275]. Miscanthus can maintain high photosynthetic rates followed by high biomass production [276]. As a perennial grass, it is suitable for various climates and has high water and nutrient use efficiencies. It is cultivable on marginal land without irrigation or heavy fertilization and is considered a leading energy crop [252].

3.2.7. Agroecological zoning

The main objective of this phase of the study is to determine optimal agricultural production areas in Ecuador within an agroecological zoning framework for each crop selected.

The zonification performed as described in Figure 16 considered the following criteria: a) Geopedological, including geomorphology, physical and chemical properties of the soils; b) Climatic, including temperature and precipitation; c) Crop requirements information, including edaphic, physical and chemical and climatic requirements; and d) Production systems to be excluded: food security crops, ecological interest areas, anthropic areas.

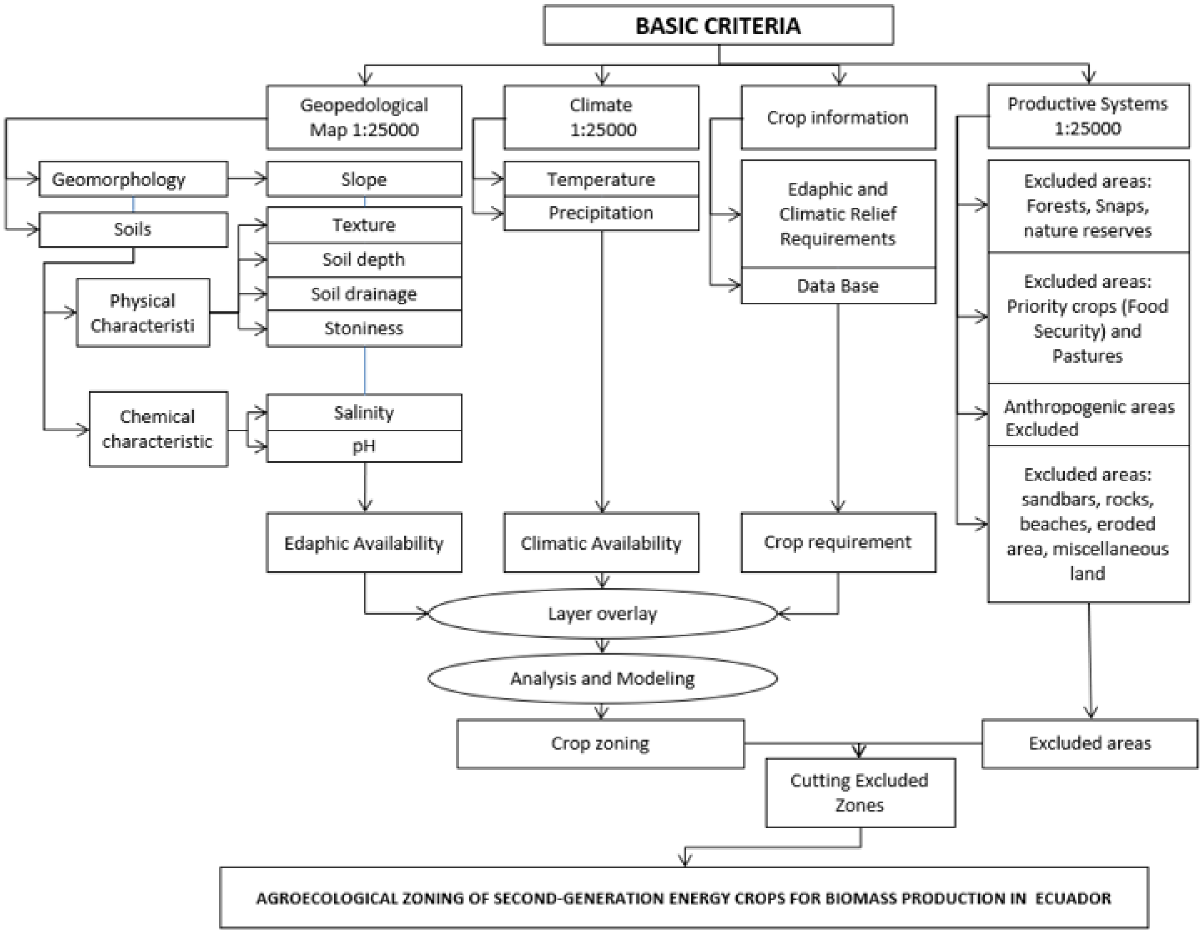

Figure 16. Agroecological zoning definition process for bioenergy crops in Ecuador

3.2.7.1. Geopedological and climatic variables

The basic criteria structure is described in Figure 16. The variables considered in the agro-ecological zoning are:

- Biophysics variables: Slope, stony, texture, pH, drainage, salinity, effective depth, most of these physical and chemical characteristics are obtained in the geopedological map.
- Climatic variables: Temperature, precipitation is integrated through the isohyetal and isotherms maps, containing historical data provided by meteorological stations in the country.
- Geopedological and climatic maps scale 1:25000 were used and processed in geographic information system software QGIS.

These maps were developed in the project: "Generation of geoinformation for the management of the territory and valuation of rural lands in the Guayas river basin, scale 1: 25000" implemented by the Ministry of Agriculture of Ecuador [277].

3.2.7.2. Agroclimatic requirements of selected crops

Biophysics and climatic variables for each of the selected crops were obtained from a bibliographical review; sources are described in Table 20.

Table 20. Agroclimatic requirements of selected crops

Common name	**Giant Reed**	**Hemp**	**Miscanthus**	**Bamboo**	**Eucalyptus**	**Pine**
Scientific Name	*Arundo donax L.*	*Cannabis sativa*	*Miscanthus spp.*	*Bambusa balcooa*	*Eucalyptus globulus*	*Pinus patula*
Family	Poaceae	Cannabaceae	Poaceae	Poaceae	Myrtaceae	Pinaceae
Slope (%)	0 to 5	2 to 25	0 to 25	0 to 40	2 to 25	2 to 25
Soil texture*	1 to 13	2, 3, 4, 5, 8, 9, 10, 11	3, 4, 5, 7, 8, 9, 10	8 to 12	3, 4, 5, 7, 8, 9, 10, 11, 12	2 to 11
Effective soil depth**	2 to 5	4 to 5	4 to 5	4 to 5	4 to 5	4 to 5
Soil drainage	Excesive, Good, Moderate, Poorly drained	Good, Moderate	Good, Moderate	Good, Moderate	Good, Moderate	Good, Moderate
Soil stony	no stones, very few stones, few stones	no stones, very few stones, few stones	no stones, very few stones, few stones	no stones, very few stones, few stones	no stones, very few stones, few stones	no stones, very few stones
Optimal pH	>5.5 to 8.5	>5.5 to 7	>5.5 to 7	5 to 6.5	5.5 to 7	5 to 6.5
Optimal temperature (°C)	16 to 24	6 to 26	12 to 25	22 to 28	10.8 to 18	10 to 19
Precipitation (mm)	300-2000	600-1500	600 to 1400		500 to 1500	700 to 1200
Salinity (dS/m)	<2 to 16	<2	<2	<2	<2	<2
Sources	[278–280]	[246, 265, 266, 276]	[270, 277–279]	[254, 280, 281]	[287–289]	[240, 285, 286]

* Soil Textures: sand (1), loamy sand (2) sandy loam (3), loamy (4), silty loam (5), silty(6), clay-sandy loam(7), loamy clay (8), silty clay loam (9) clay-sandy (10), clay-silty (11), clay (12), heavy clay (13).

** Effective soil depth: very shallow soil (1), surface soil (2), shallow soil (3), moderately deep soil (4), deep soil (5).

3.2.7.3. Excluded systems

The proposed methodology aims to exclude areas that have ecological importance or are currently used for agricultural production, anthropic zones, and pastures with economic importance.

3.2.7.3.1. Excluded Productive Systems

Agricultural production areas

Priority crops: where identified based on their importance considering the following groups:

a) **Export crops:** Crops for human consumption for exporting interests were identified using secondary information from the Central Bank of Ecuador [10].
b) **Food sovereignty crops**: The list of agricultural products commercialized in Ecuador markets was obtained and defined as food security, the information was obtained from the SIPA project (MAG) [292].

Agricultural land use map was obtained at 1: 25000 scale from the Ministry of Agriculture of Ecuador (MAG).

In this regard, the proposed methodology excluded from the zoning areas dedicated to the agricultural production of 89 crops described in Annex 4.

Pastures

Pastures excluded from the study are defined in the land use classification as a business and mercantile pastures which determine its economic importance for livestock production. Pastures defined as marginals have been consider within the zoning exercise because of their low profitability.

3.2.7.3.2. Excluded ecological importance zones

Ecological importance zones inside PANE

The study aims to avoid interference with ecological importance areas; in this regard, the following land uses were excluded from the study: National Reserve Zones, Protective Forests, Paramos, zones declared by the State as reserves. The information was obtained from the natural Heritage map of national areas of Ecuador (PANE by its acronyms in Spanish) developed by the Ministry of Environment of Ecuador [293].

Ecological importance zones outside PANE

Disturbance or alteration of ecological systems is categorized as high, moderate, and low. In this study, there were also excluded zones of ecological importance that are not considered in PANE presenting moderate or low disturbance within the following categories of land use: Forest, Mangrove, Paramo, Shrub Vegetation and Scrub Zones considering their disturbance level were also excluded. This information was obtained through the National Coverage and Land Use Map developed by the Ministry of Agriculture (MAG by its acronyms in Spanish).

3.2.7.3.3. Excluded Anthropic zones

This category considers all anthropic areas as infrastructure, roads, archaeological sites, landfills, etc... These areas were excluded from the study and described in Annex 2.

Areas with water sources

The excluded water sources are artificial water bodies, natural water bodies, residual water reservoirs, freshwater reservoirs, cienega, swamp, lava flow, glacier, lake/lagoon, snow and ice, and rivers.

Zones classified as miscellaneous.

Many areas do not have soil or are very shallow; consequently, they support little vegetation, areas with no greater use; the rocky outcrop is an example. Names in miscellaneous areas are used in the same way as names in soil taxonomy when identifying mapping units [294]. These excluded areas are rocky outcrop, flood area, area in the process of erosion, eroded area, saline area, sandbank, wasteland.

3.2.8. Map overlay

Within a Geographic Information System (SIG), the union between the geopedological map and the isotherm and isohyet maps were performed. This step merged the information layers of the different maps to produce a fourth map with polygons containing geopedological and climate information. This process facilitates the creation of useful information for the development of the agroecological model. Finally, areas mentioned in 3.2.7 were excluded using a GIS software tool. This process is illustrated in Figure 17, while Figure 18 provides an idea of the scale used in the study.

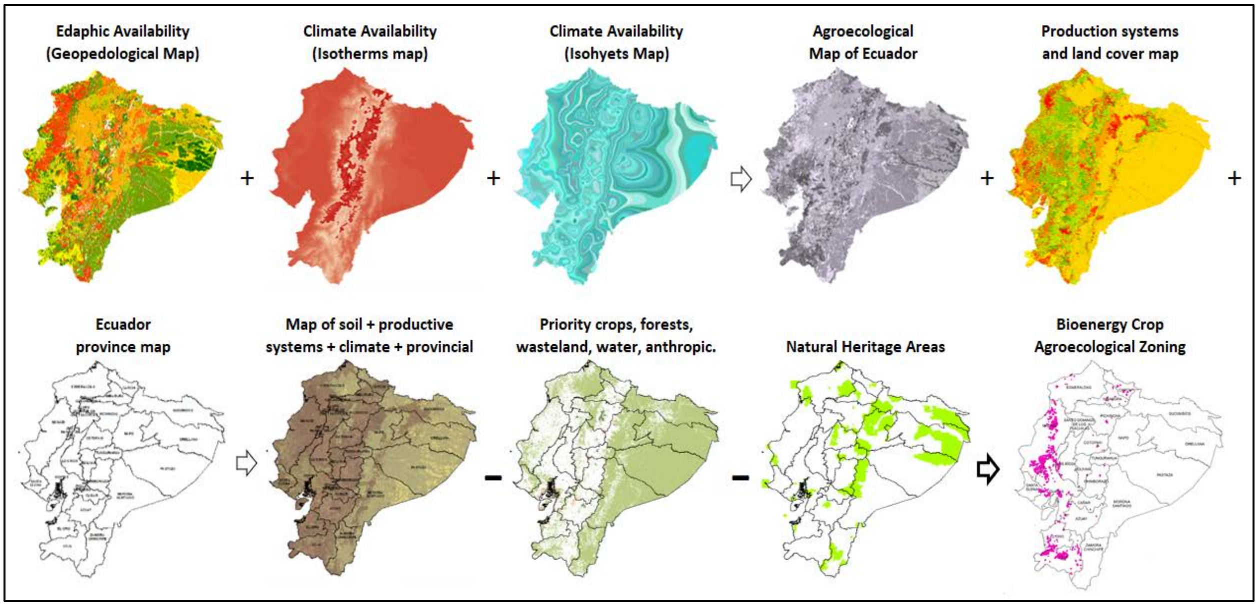

Figure 17. Maps overlying to identify available land for bioenergy production in Ecuador

Figure 18. Illustrative example of areas identified as suitable scale 1:125000

3.2.9. Net energy yield estimation

To determine the potential net energy yield of the estimated bioenergy feedstock production, a literature review was performed to determine the efficiency of electricity technologies available for biomass.

Three routes are mainly available for power generation from biomass. These are: a) Biomass combustion-turbine cycle; b) Gas turbine-based solutions; and c) Hybrid solutions. In this study, four main technological categories were identified of biomass plants including reference values for size and efficiency: Steam power plants, Externally-fired gas turbines, Biomass integrated gasification, Combined Cycle [295–298].

The following performances and efficiencies of typical plant configurations using biomass as fuel considered are shown in Table 21.

Table 21. Typical biomass plant configurations and efficiencies

Configuration	Lower limit Efficiency (%)	Upper limit Efficiency (%)
Steam power plants (backpressure turbines) 20-25 MW	10	20
Steam power plants (condensing turbines) 5–50 MW	22	28
Externally-fired gas turbines 5–25 MW (simple cycle)	25	30
Externally-fired gas turbines 10–30 MW (combined cycle)	30	40
Biomass integrated gasification 40–60 MW simple cycle	21	25
Combined cycle 90–100 MW combined cycle	35	40

Source: Franco et al. (2003) [295]

The formula applied to calculate the potential energy production is:

$$Ney = (LCv * By) * Te \qquad \text{Equation 1}$$

Where:

- Ney, net energy yield (kcal/ha)
- LCv, lower caloric value of biomass (kcal/kg)
- By, biomass yield in dry basis (kg/ha)
- Te, combined technology efficiency. Combined technology efficiency is a resulting energy efficiency figure that gathers all the referential conversion processes efficiency percentages. Biomass pretreatment and chipping stages are neglected in this calculation

Therefore, to determine the potential energy yield per crop the following formula was applied:

$$Eyc = Ney * Nha \qquad \text{Equation 2}$$

Where:

- Eyc, energy yield per crop per year (kcal/ha·year)
- Nha, number of hectares (ha)

In the case of overlapped areas, crops with the highest energy yield per hectare per year were prioritized over the rest, e. g. if the same area was shared by Giant reed, Miscanthus, and eucalyptus; Giant reed was prioritized since it has the highest energy yield.

4. Results

In this chapter, the obtained results from the studies performed are presented. The results are divided into sections. Regarding the first topic, Bioenergy life cycle assessment on islands are presented in Section 4.1. The next topic of research Bioenergy potential agro-ecological zoning study results are detailed in Section 4.2.

4.1. Life Cycle Assessment of Bioenergy in Islands

4.1.1. Impact of categorization results

The main comparative results from method CML 2001 for RPO and WCO LCA per impact category are shown in Table 22, while the comparison in percentages is provided in Figure 19. The results per contributor are illustrated as well in Table 21.

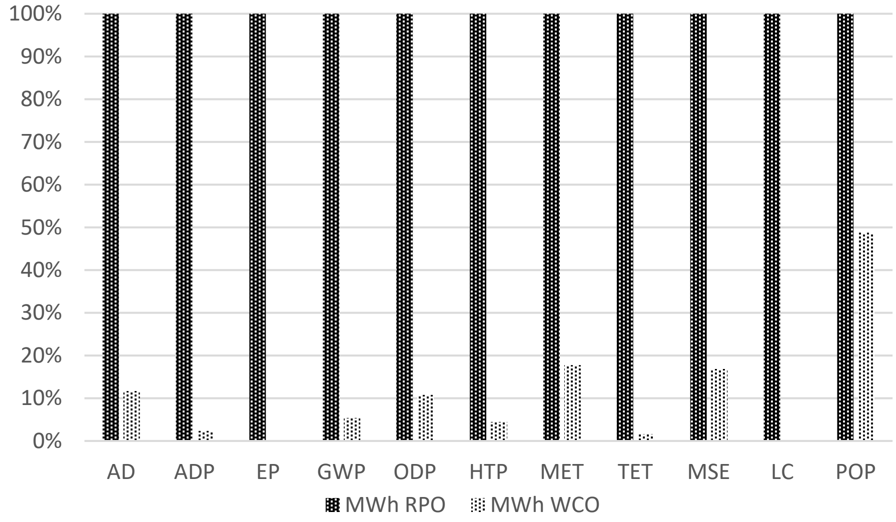

Figure 19. Comparison of the characterization results of refined palm oil (RPO) vs. waste cooking oil (WCO) based electricity generation in Galápagos

Table 22. Main impact categorization results per 1 MWh derived from refined palm oil (RPO) and waste cooking oil (WCO)

Impact Category	Abbreviation	Unit	MWh RPO	MWh WCO
Marine sediment ecotoxicity	MSE	kg 1,4–DB eq	1.6×10^2	2.7×10
Photochemical oxidation	POP	kg C_2H_4 eq	7.6×10^{-1}	3.7×10^{-1}
Land competition	LC	m^2a	1.0×10^2	2.3×10^{-1}
Terrestrial ecotoxicity	TET	kg 1,4–DB eq	2.1×10^{-1}	3.3×10^{-3}
Marine aquatic ecotoxicity	MET	kg 1,4–DB eq	1.4×10^2	2.5×10
Human toxicity	HTP	kg 1,4–DB eq	1.7×10^2	7.7
Ozone layer depletion	ODP	kg CFC–11eq	1.6×10^{-5}	1.7×10^{-6}
Global warming	GWP	kg CO_2 eq	4.5×10^2	2.4×10
Eutrophication	EP	kg PO_4–eq	7.9	1.6×10^{-2}
Acidification	AP	kg SO_2 eq	3.6	1.1×10^{-1}
Abiotic depletion	ADP	kg Sb eq	1.7	2.3×10^{-1}

Regarding global warming (GWP), the life cycle of WCO decreases this indicator by 94.6% compared with RPO. The primary source of greenhouse gases in the RPO production cycle is methane production from wastewater and landfill emissions in the oil extraction phase. In terms of abiotic depletion, WCO performs 97% better than RPO because of the reduced use of processing facilities and the avoidance of fertilizers (mainly urea) in its production. RPO performed worse than WCO in terms of acidification, mainly because of ammonia release derived from the use of urea as a fertilizer and the use of pesticides in the agricultural production phase. Regarding eutrophication potential, RPO presents a 90% greater contribution than WCO because of the chemical oxygen demand (COD) and nitrogen present in the wastewater at the extraction phase. On the other hand, WCO performs 7.56 times better than RPO regarding ozone depletion over five years. In terms of human toxicity at 20 years, WCO performs 95% better than RPO. The results show 27% better performance of WCO when compared with RPO regarding photochemical oxidation. In terms of terrestrial and marine ecotoxicity, mainly because of the use of herbicides, RPO performs 98% and 71% worse than WCO, respectively. The results comparison for each impact category is illustrated in Figure 19.

4.1.2. Contribution analysis

4.1.2.1 Refined palm oil

Figure 20 shows contribution analysis per process for RPO-based electricity generation.

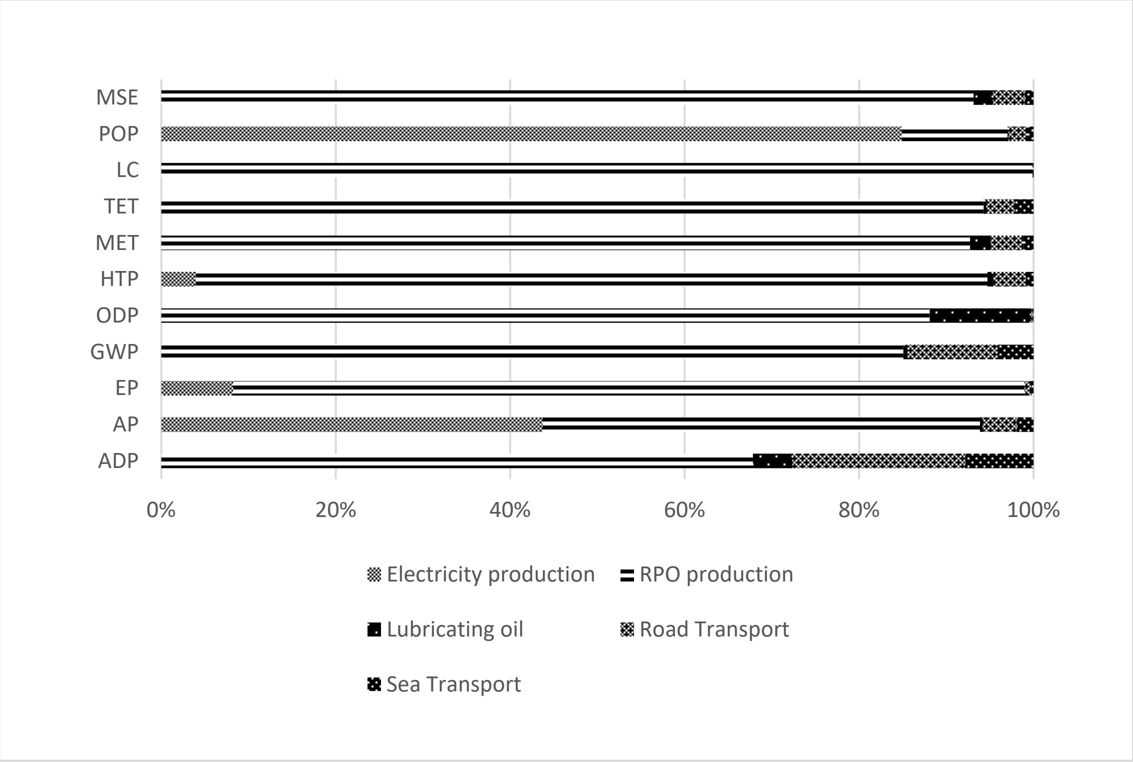

Figure 20. Contribution analysis per process for refined palm oil (RPO) based electricity generation

As shown in Figure 20 the main contributor to global warming potential is the production cycle of RPO, as mentioned, mainly because of the agricultural and industrial phases. RPO production is also a major contributor to most of the impact categories.

Electricity generation is contributing to 83% of the total photochemical oxidation and almost 50% of the acidification potential. Road transport accounts with a 20% of abiotic depletion, 10% of global warming potential and reduced contribution in other categories, while sea transportation has an 8% contribution in ADP and minimal contributions in other categories. Finally, lubricating oil accounts with 4%of ADP, 10% of Ozone layer depletion potential and contributions lower than 2% in other categories

4.1.2.2 Waste cooking oil

Figure 21 shows contribution analysis per process for WCO-based electricity generation.

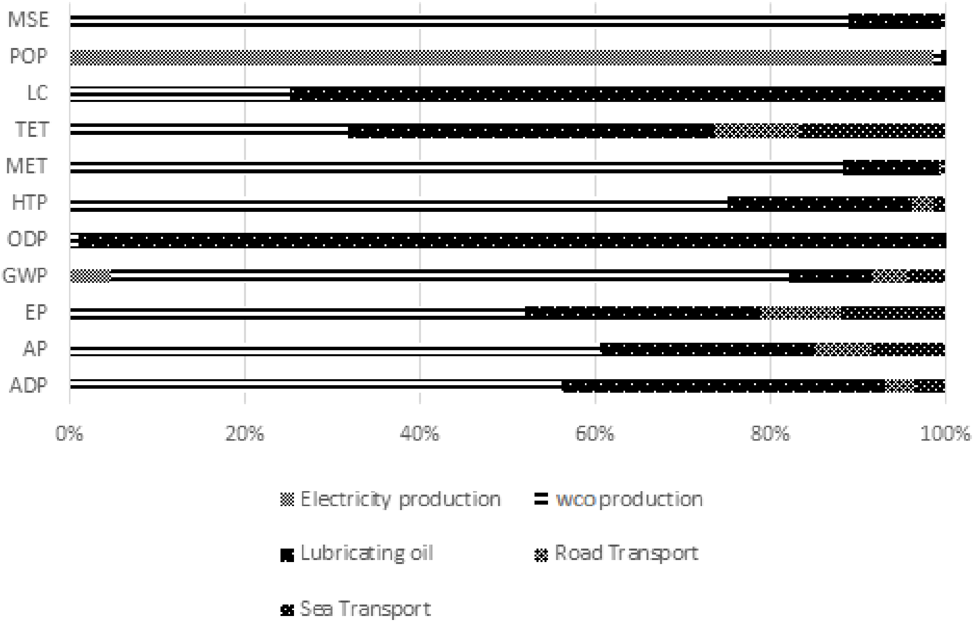

Figure 21. Contribution analysis per process for waste cooking oil (WCO) based electricity generation

In WCO electricity generation, as shown in Figure 21, the greatest contributor is the cleaning process of used WCO contributing with a 95% of MSE and MET, 90% of the total GWP, 62% of AP and 57% of ADP.

Electricity production presents a 98% contribution on POP while Sea transportation accounts with 98% of total ODP contribution, 75% of LC, and significant presence in all the remaining impact categories. Finally, road transportation accounts with lower contributions mainly in TET, EP, AP and ADP.

4.1.3. Emission measurement in electricity generation results

Results from this section of the study are shown in Table 23 and data measurement compilation is presented in Annex 4. The resulting data is consistent with the registered by Sauza et al. (2012) [299].

Table 23. Emissions from the generation of 1 MWh out of diesel, refined palm oil (RPO) and waste cooking oil (WCO)

Fuel	**CO**	**CO_2**	**HC**
	kg/MWh	kg/MWh	kg/MWh
Diesel	10.977	322.076	28.8
RPO	23.63	483.85	86.3
WCO	13.48	499.14	37.4

Carbon monoxide (CO) emissions showed a lower concentration in assays performed with diesel fuel. The reason associated with this fact can be related to the physical properties of the fuel that show their effect during its use in an internal combustion engine [300]. In general terms, diesel fuel has been reported to contain a larger amount of energy per mass or volume unit than vegetable oils [301]. In addition, WCO registered a lower CO emission factor than RCO. In such a context, this issue can be associated with the chemical modification that cooking oil may suffer during its use. These changes can affect their properties such as viscosity or calorific value which are also relevant for determining its performance in an internal combustion engine [301].

The CO emission figures registered during the experimental assay's concord the CO_2 figures as well. This issue can be highlighted since the diesel appears as the most efficient choice in terms of energy and WCO showed a better performance when compared to RCO. In this context, it can be affirmed that WCO is a better alternative as fuel despite it is considered a waste material.

Regarding hydrocarbon (HC) content, a trend like CO was found. Despite diesel fuel has no oxygen content in its composition, other properties such as viscosity (determining during fuel injection and air-fuel blending inside the engine [302], and calorific value established that the combustion efficiency reached better results than the assayed oxygenated fuels. In addition, WCO appeared as a better fuel when compared to RPO. This issue can be associated to the partial hydrogenation that oils suffer during the cooking process due to their contact to water at high temperatures [303] Saturation implies augmenting the hydrogen content in oil composition, hence its calorific value and viscosity increases in a similar rate [304]. Electricity generation test results show a fuel consumption of 0.216 l/kWh for WCO, 0.328 l/kWh for RPO, and 0.162 l/ kWh for diesel.

4.2. Agroecological zoning of second-generation energy crops

4.2.1. Bamboo

According to the zoning results, there exist 28,352.39 ha available to produce bamboo in Ecuador (Table 24, Figure 22).

The agroecological requirements for the cultivation of Bamboo are: soils with slopes ranging from 0% to 40%, textures from clay loam to clay, moderate to deep depth, few stony to frequent stones, good drainage to moderate, not saline, acidic to slightly acidic pH; and temperatures ranging from 22 to 28 °C, with average annual rainfall from 2,300 to 3,000 mm.

In Ecuador, Esmeraldas province presents 6,324.53 ha, the largest available area for bamboo production, mainly in Quinindé canton, followed by Santo Domingo de los Tsachilas province with 5,995.31 ha. These two provinces are located on the North Coast of Ecuador. The following crops and vegetation are representative of the traditional land use of these cantons: banana, moderately altered humid forest, moderately altered humid scrub, highly altered humid herbaceous vegetation, abacá, cultivated pasture, highly altered humid scrub, highly altered humid forest, and palm oil.

The third-largest area is located in Morona Santiago province in Morona, Limón Indanza and San Juan Bosco cantons, followed by Sucumbíos province in the Northeastern region of the country [277].

In general, these areas are characterized by warm, humid climates, acid soils, well-drained soils, and frequent rains. Provinces located in the highland's present smaller optimal areas for bamboo cultivation, mainly in warm microclimates.

Table 24. Optimal area to produce bamboo in Ecuador

Province	**Optimal area (ha)**
Pichincha	4.23
Manabí	331.62
Zamora Chinchipe	669.67
Bolívar	926.46
Imbabura	1,160.66
Los Ríos	1,442.55
Santa Elena	1,863.04
Tungurahua	2,,832.70
Sucumbíos	2832.70
Morona Santiago	3,968.90
Santo Domingo de los Tsáchilas	5,995.31
Esmeraldas	6,324.53
Total	**28,352.39**

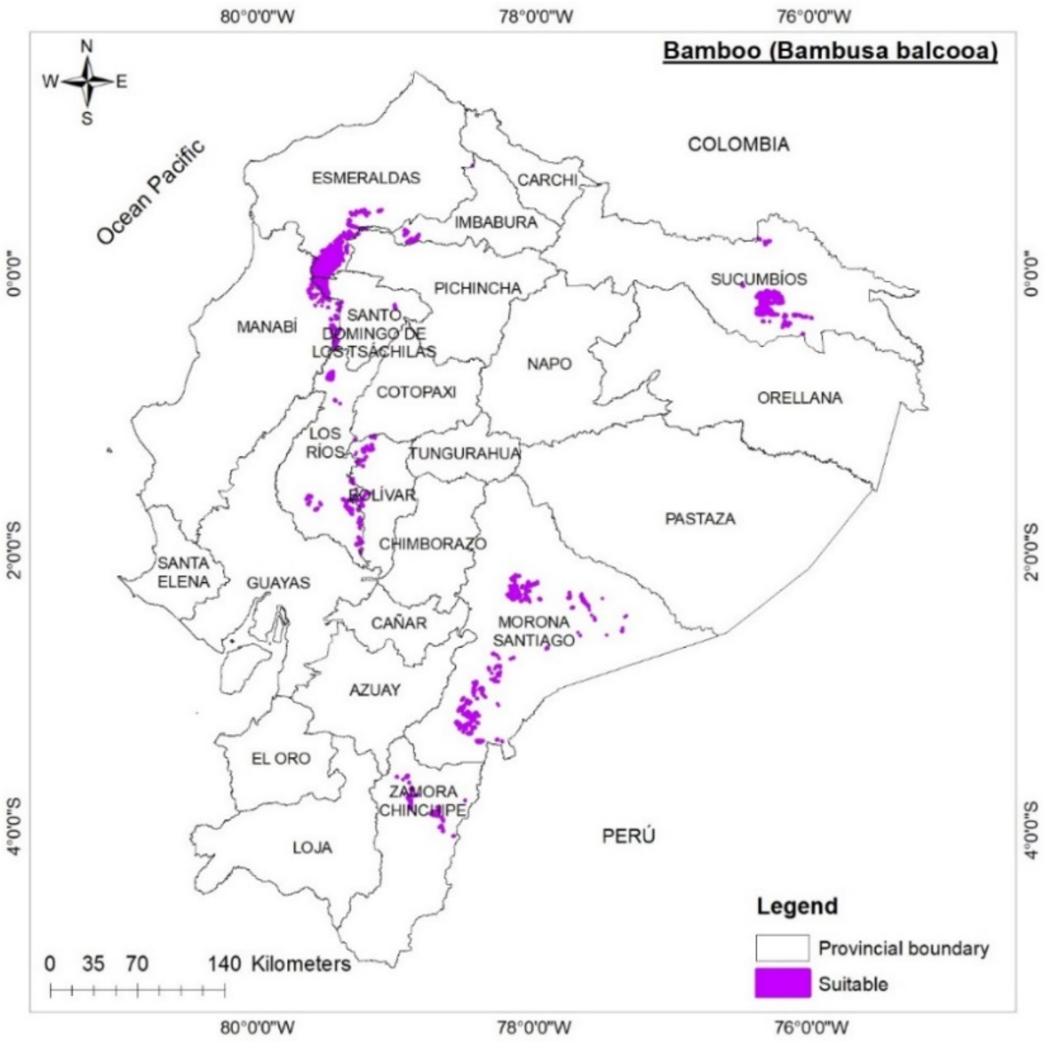

Figure 22. Available surface for bamboo production in Ecuador

4.2.2. Hemp

According to the agroecological zoning results there exist 17,269.31 ha in Ecuador available to produce Cannabis sativa (Table 25, Figure 23). The agroecological requirements for the cultivation of hemp (Table 19) are soils with slopes ranging from 0% to 25%, silty loam, silty clay loam, and clay-silty, textures, moderate to deep soil, few stony to frequent stones, good drainage to moderate, not saline, acidic to neutral pH; and temperatures ranging from 6 to 26 °C, with average annual rainfall from 600 to 1,500 mm.

The study identified 23,170.31 ha available for hemp production as a bioenergy feedstock in Ecuador. Guayas province accounts for the larger area with 11,033.38 ha in the following cantons: Naranjal, Yagual, Yaguachi, Duran Balzar, Santa Lucia, Colimes, and Guayaquil. The following crops and vegetation are representatives of the land use of these cantons: teak, cultivated grass, cultivated grass with the presence of trees, rice, dry herbaceous vegetation moderately altered, corn, palm oil, fallow, dry forest heavily altered, herbaceous wetland vegetation severely altered, agricultural land without cultivation, dry forest moderately altered, teak, very altered dry scrub, moderately altered dry scrub, severely altered dry herbaceous vegetation.

Manabí province presents the second larger area with 5,449.94 ha, on Pedernales, Flavio Alfaro, Chone, Santana, Olmedo Jipijapa, 24 de Mayo y Pajan cantons. The following crops and vegetation are representatives of the land use of these cantons: saman, medium altered humid herbaceous vegetation, corn, achiote, miscellaneous fruit trees, tangerine, very altered dry herbaceous vegetation, raft, medium altered dry scrub, fallow, cultivated pasture with the presence of trees, teak, very altered dry scrub, medium altered humid scrub, very altered humid herbaceous vegetation, very altered dry forest, undifferentiated miscellaneous, bamboo, medium altered dry forest, very altered humid shrub cultivated pasture, very altered humid forest, moderately altered humid forest.

The province with the third larger area is Loja, mainly in Puyango and Paltas cantons. The land use on these cantons is dominated by corn production, low to medium altered dry forest, and cultivated pastures. The vegetation present in these provinces is characteristic of dry climates with high luminosity, non-saline soils, and low slopes.

It is important to remark that small spots are identified within dry inter-Andean valleys among the Andean mountain range. Furthermore, in the Amazonian region, any area was identified due to its excessive precipitation and acid soils.

Table 25. Optimal area to produce hemp in Ecuador

Province	Optimal area (ha)
Azuay	291.60
Bolívar	10.70
Cañar	0.01
Carchi	221.30
Chimborazo	306.87
Cotopaxi	280.14
El Oro	1,003.56
Esmeraldas	906.78
Guayas	11,033.38
Imbabura	118.12
Loja	2,690.29
Los Ríos	171.25
Manabí	5,449.94
Pichincha	142.09
Santa Elena	544.17
Tungurahua	0.11
Total	**23,170.31**

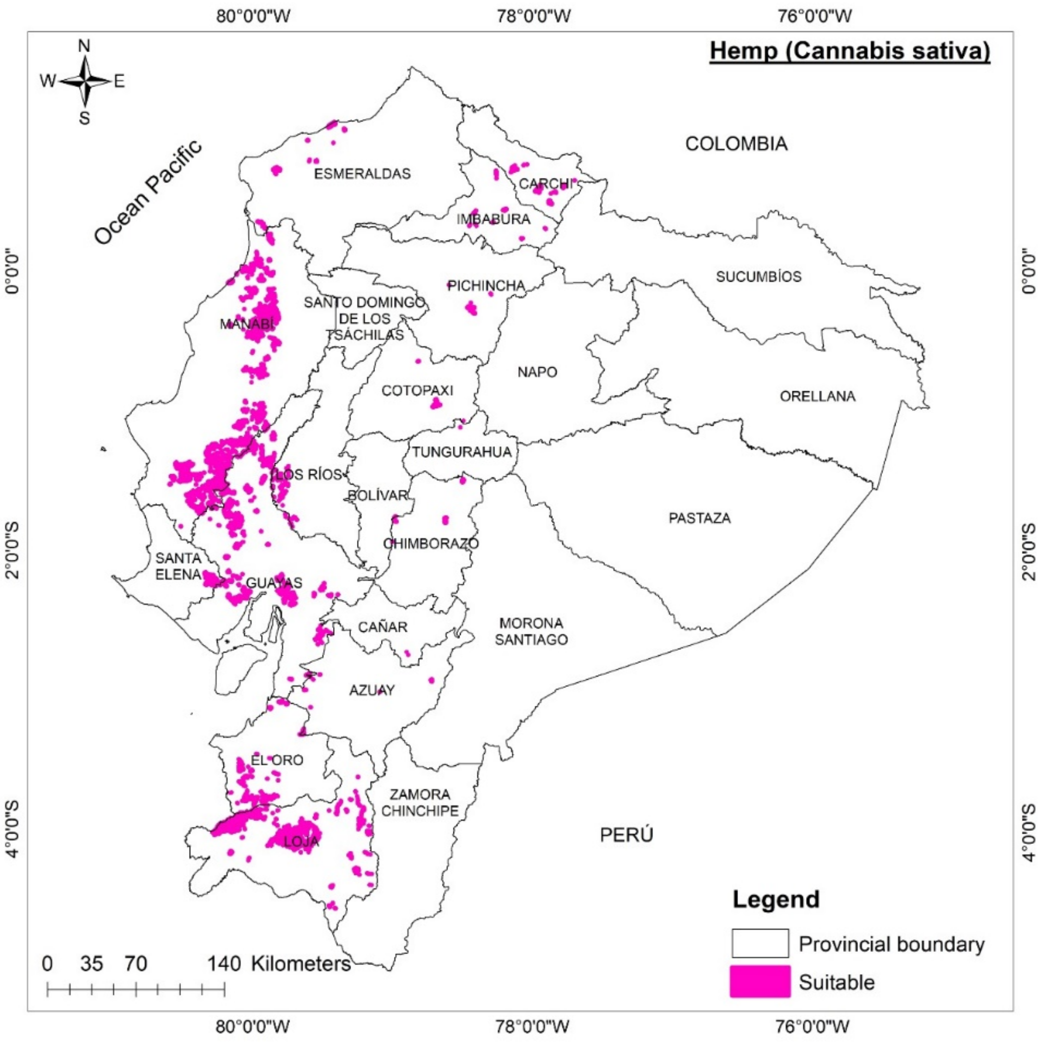

Figure 23. Available surface for hemp production in Ecuador

4.2.3. Eucalyptus

According to the agroecological zoning results, 39,550.53 ha in Ecuador are available to produce eucalyptus (Table 26, Figure 24).

The agroecological requirements for the cultivation of eucalyptus are: soils with slopes ranging from 0% to 25%, sandy loam, loamy, silty loam, clay-sandy loam, loamy clay, silty clay loam, clay-sandy, clay-silty, clay, textures, moderate to deep depth, few stony to frequent stones, good drainage to moderate, not saline, acidic to neutral pH; and temperatures ranging from 10.8 to 18 °C, with average annual rainfall from 500 to 1,500 mm.

Pichincha province has the largest available area with 10,804.46 ha in Pichincha, Mejia, Pedro Moncayo, and Cayambe cantons. The following crops and vegetation are representatives of the land use of these cantons: very altered dry herbaceous vegetation, medium altered humid forest, medium altered dry scrub, pine, Andean summer flowers, miscellaneous cereals, corn, cultivated pasture with the presence of corn, medium altered moist scrub, very altered humid scrub, cultivated pasture, eucalyptus, short cycle miscellaneous, and roses.

Cotopaxi with 13,148.68 ha is the second largest province with available land for producing the crop. The main cantons are Latacunga, Pujilí, Salcedo, Saquisilí, and Sigchos. In these cantons, the predominant land use is medium altered dry herbaceous vegetation, medium altered wet herbaceous vegetation, very altered humid herbaceous vegetation, medium altered wet scrub, cultivated pasture, pine, roses, short cycle miscellaneous, corn, eucalyptus, corn, and cultivated grass.

The third province with the largest available land is Azuay, with 5,297.75 ha in Cuenca, Girón, Gualaceo, Paute, Chordeleg, El Pan, and Guachapala cantons, in which the current land use is: medium altered shrubby paramo, medium altered humid forest, very altered humid forest, corn, pine, Andean summer flowers, very altered humid herbaceous vegetation, medium altered humid herbaceous vegetation, eucalyptus, severely altered humid thicket, miscellaneous cultivation of corn, cultivated pasture, medium altered wet scrub.

This vegetation is characteristic of cold and temperate climates, low precipitation, and wide soil ranges. These areas are mainly present in the inter-Andean mountain range.

Table 26. Optimal area to produce eucalyptus in Ecuador

Province	Optimal area(ha)
Azuay	5,297.75
Bolívar	856.26
Cañar	1,531.19
Carchi	647.76
Chimborazo	3,393.71
Cotopaxi	6,440.33
El Oro	210.21
Imbabura	4,794.79
Loja	1,211.44
Morona Santiago	47.32
Napo	27.49
Pichincha	10,804.46
Tungurahua	1,153.34
Zamora Chinchipe	3,134.47
Total	**39,550.53**

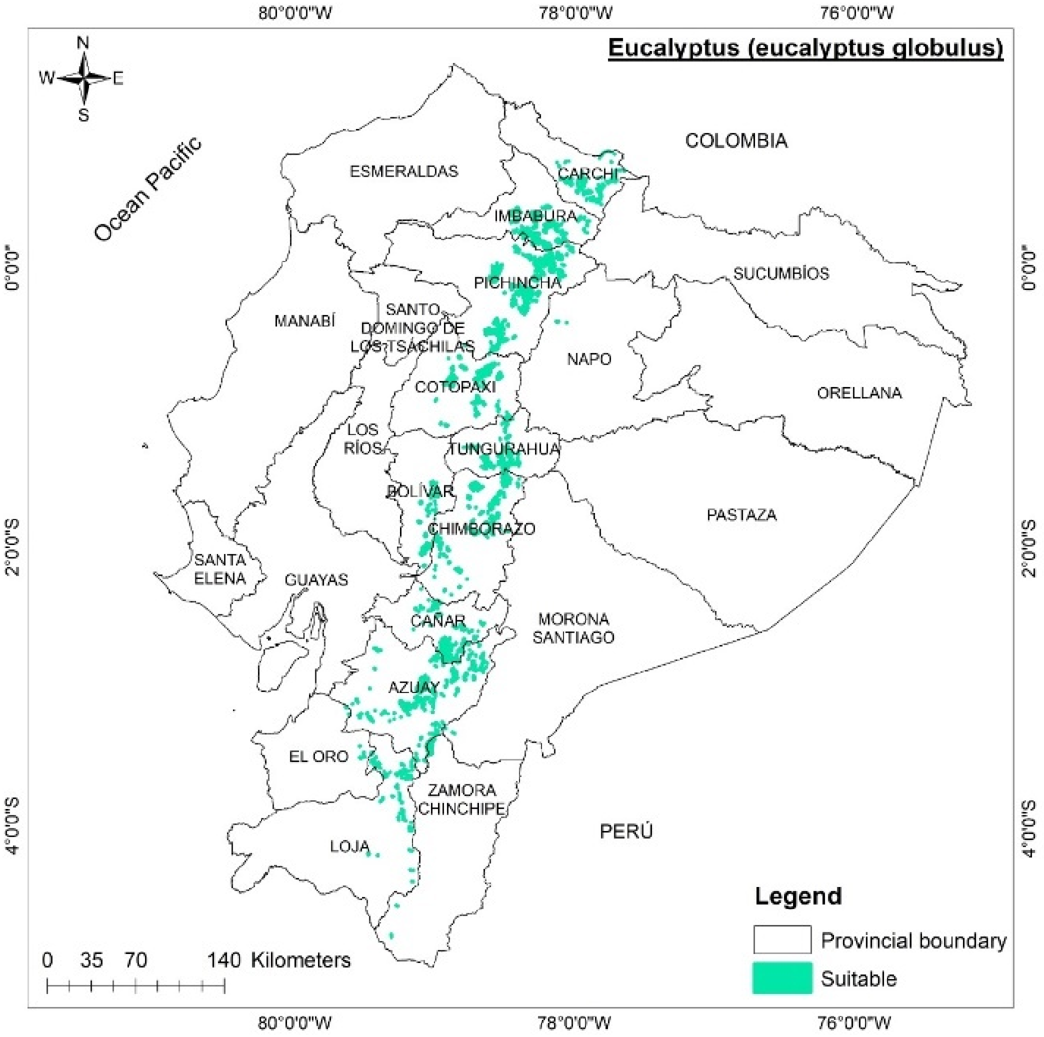

Figure 24. Available surface for eucalyptus production in Ecuador

4.2.4. Giant reed

According to the agro-ecological zoning results, there exist 85,777.66 ha in Ecuador are available to produce Arundo donax (Table 27, Figure 25).

The agroecological requirements for the cultivation of Giant reed are soils with slopes ranging from 0% to 5%, textures from sand to heavy clay, superficial to deep depth, no stony, few stony and frequent stones, excessive, good, and moderate drainage, not to very saline, slightly acidic to alkaline pH; and temperatures ranging from 16 to 24 ° C, with average annual rainfall from 300 to 2,000 mm.

The study identified 85,777.66 ha. available for Giant reed production as a bioenergy feedstock in Ecuador. Loja province accounts for the larger area with 25,296.27 ha in the following cantons: Puyango, Pindal, Paltas, Espindola, Loja, Macara, Olmedo, and Quilanga. The following crops and vegetation are representatives of the land use of these cantons: banana, very altered shrubby paramo, coffee, pine, sugarcane, fallow, rice, eucalyptus, peanuts, very altered humid forest, medium altered humid scrub, medium altered humid forest, very altered humid scrub, cultivated pasture with the presence of trees, undifferentiated miscellaneous, very altered dry herbaceous vegetation, medium altered dry scrub, very altered wet herbaceous vegetation, very altered dry scrub, medium altered dry forest, very altered dry forest, corn, cultivated pasture.

The second-largest area with 20,078.43 ha is located on Manabí province in the following cantons: Junin, Jipijapa, 24 de Mayo and Pajan. In these cantons, the current land use presents pachaco, toquilla straw, cultivated grass, cultivated grass with the presence of trees, cultivated grass with the presence of tangerine, teak, agricultural land without cultivation, very altered humid herbaceous vegetation, very altered dry herbaceous vegetation.

Due to its adaptability to a wide range of soil types, precipitation, drainage, and pH, it has a presence in almost all country zones with a prevalence in dry areas.

Table 27. Optimal area to produce Giant reed in Ecuador

Province	**Optimal area (ha)**
Azuay	3,813.46
Bolívar	599.11
Cañar	982.73
Carchi	1,497.80
Chimborazo	1,086.92
Cotopaxi	103.87
El Oro	2,391.74
Esmeraldas	1,219.76
Guayas	2,586.48
Imbabura	5,485.93
Loja	25,296.27
Los ríos	26.74
Manabí	20,078.43
Morona Santiago	7,526.17
Pichincha	6,602.02
SantaElena	1,103.24
Santo Domingo de los Tsáchilas	17.39
Sucumbíos	0.35
Tungurahua	140.45
Zamora Chinchipe	5,218.80
Total	**85,777.66**

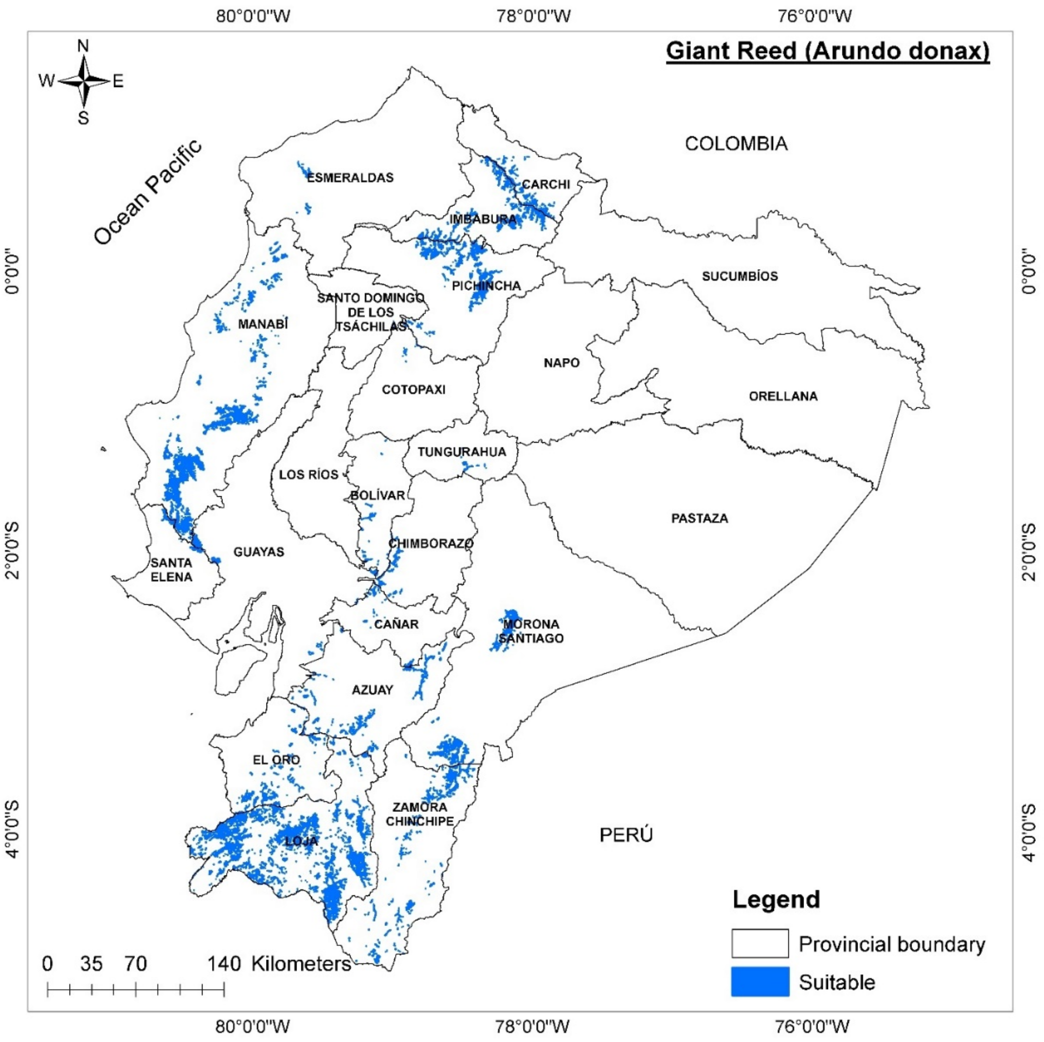

Figure 25. Available surface for Giant reed production in Ecuador

4.2.5. Pine

According to the agro-ecological zoning results, 16,877.29 ha in Ecuador are available to produce pines (Table 28, Figure 26).

The agroecological requirements for the cultivation of pine are soils with slopes ranging from 0% to 40%), loamy sand, sandy loam, loamy, silty loam, silty, clay-sandy loam, loamy clay, silty clay loam, and clay-sandy textures, moderate to deep depth, few stones, good to moderate drainage, not saline, acidic to slightly alkaline pH; and temperatures ranging from 10 to 19 °C, with average annual rainfall from 700 to 1,200 mm.

Pichincha province presents the largest available area 13,344.45 ha. The main identified cantons with available areas are Distrito Metropolitano de Quito, Cayambe, Mejía, and Pedro Moncayo. The current land use in these cantons is very altered humid herbaceous vegetation, Andean summer flowers, very altered humid forest, barley, medium altered shrub paramo, pasture cultivated with the presence of corn, pine, medium altered humid forest, corn, cereal miscellaneous, very altered humid scrub, humid shrub medium altered, cultivated grass, eucalyptus, short cycle miscellaneous, roses.

In Imbabura province, the second-largest area was identified with 8,843.38 ha mainly in the following cantons: Ibarra, Antonio Ante, Cotacachi, and Otavalo. The following crops and vegetation are representatives of the land use of these cantons: pine, wheat, protea, roses, barley, very altered dry herbaceous vegetation, very altered humid forest, short cycle miscellaneous, corn-bean, very altered humid herbaceous vegetation, moderately altered humid forest, moderately altered humid shrub, very altered humid shrub, eucalyptus, cultivated grass, corn.

The third-largest province with available land is Cotopaxi, with 5,787.72 ha within Latacunga, Pujilí, Salcedo, Saquisilí, and Sigchos cantons. The mainland use in those cantons is cypress, very altered dry scrub, grass cultivated with the presence of trees, medium altered dry herbaceous vegetation, medium altered dry scrub, miscellaneous of cereals, very altered moist scrub, very altered humid herbaceous vegetation, potato, scrub humid vegetation, medium altered wet herbaceous vegetation, roses, cultivated grass, short cycle miscellaneous, eucalyptus, pine, corn, cultivated grass.

Table 28. Optimal area to produce pine in Ecuador

Province	Optimal area (ha)
Azuay	4,739.62
Bolívar	1,010.70
Cañar	1,329.35
Carchi	1,332.38
Chimborazo	3,800.85
Cotopaxi	5,787.72
El Oro	168.48
Imbabura	8,843.38
Loja	1,133.28
Morona Santiago	1.26
Pichincha	13,344.45
Tungurahua	939.81
Zamora Chinchipe	2,183.14
Total	**44,614.41**

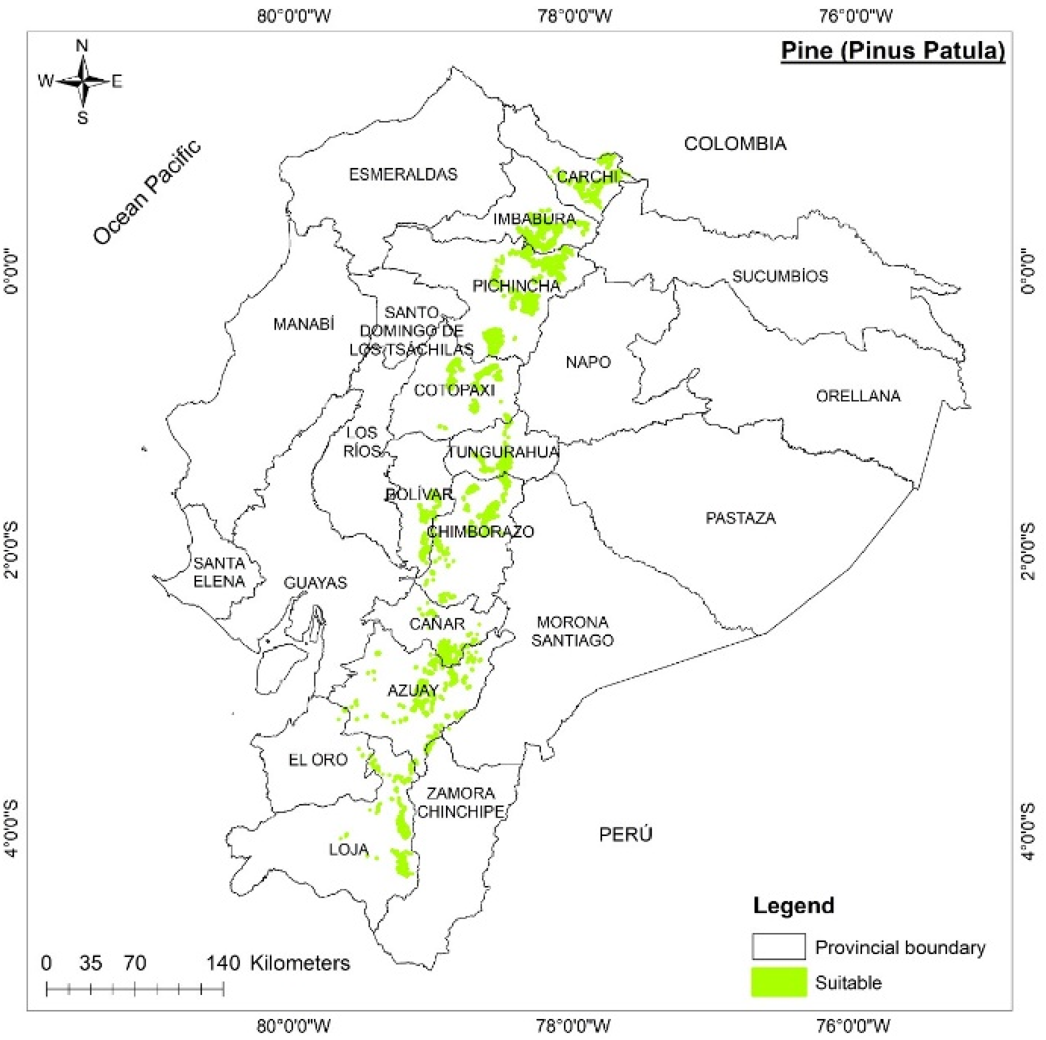

Figure 26. Available surface for pine production in Ecuador

4.2.6. Miscanthus

According to the agro-ecological zoning results, there exist 40,090.11 hectares in Ecuador available to produce Miscanthus (Table 29, Figure 27).

The agroecological requirements for the cultivation of Miscanthus are soils with slopes ranging from 0% to 25%, sandy loam, loamy, silty loam, clay-sandy loam, loamy clay, silty clay loam, clay-sandy textures, moderate to deep depth, few stony to frequent stones, good to moderate drainage, not saline, acidic to neutral pH; and temperatures ranging from 12 to 25 ° C, with average annual rainfall from 600 to 1,400 mm.

In Ecuador, the largest available area 74,367.89 ha is located in Manabí province in Portoviejo, Bolivar, Junín, Chone, Pajan, Tosagua, Santana, and 24 de Mayo cantons. The following crops and vegetation are representatives of the land use of these cantons: cocoa, banana, bamboo, coconut, raft, fallow, very altered wetland herbaceous vegetation, maize, teak, very altered humid herbaceous vegetation, medium altered humid scrub, very altered dry herbaceous vegetation, medium-dry forest altered very altered, very altered humid shrubland, medium altered dry forest, cultivated pasture with presence of trees, undifferentiated miscellaneous, very altered dry shrub, very altered humid forest, cultivated pasture, medium altered humid forest.

The second province with the available area to produce Miscanthus is Guayas with 13,148.68 ha. Mainly located in Pedro Carbo and Isidro Ayora cantons, the prevalent land use in those cantons is: corn, beans, teak, rice, fallow, medium altered dry scrub, very altered dry scrub, very altered dry forest, very altered dry herbaceous vegetation, medium altered dry forest.

These crops and vegetation respond to low precipitation, moderately acidic pH, and hot dry climates.

Table 29. Optimal area to produce miscanthus in Ecuador

Provincia	Optimal area (ha)
Azuay	4,173.33
Bolívar	810.17
Cañar	1,057.95
Carchi	1,436.61
Chimborazo	2,733.60
Cotopaxi	2,347.64
El Oro	3,106.00
Esmeraldas	2,114.97
Guayas	13,148.68
Imbabura	6,941.95
Loja	3,093.79
Manabí	16,789.72
Morona Santiago	16.06
Pichincha	10,443.76
Santa Elena	5,497.64
Tungurahua	655.79
Zamora Chinchipe	0.24
Total	**74,367.89**

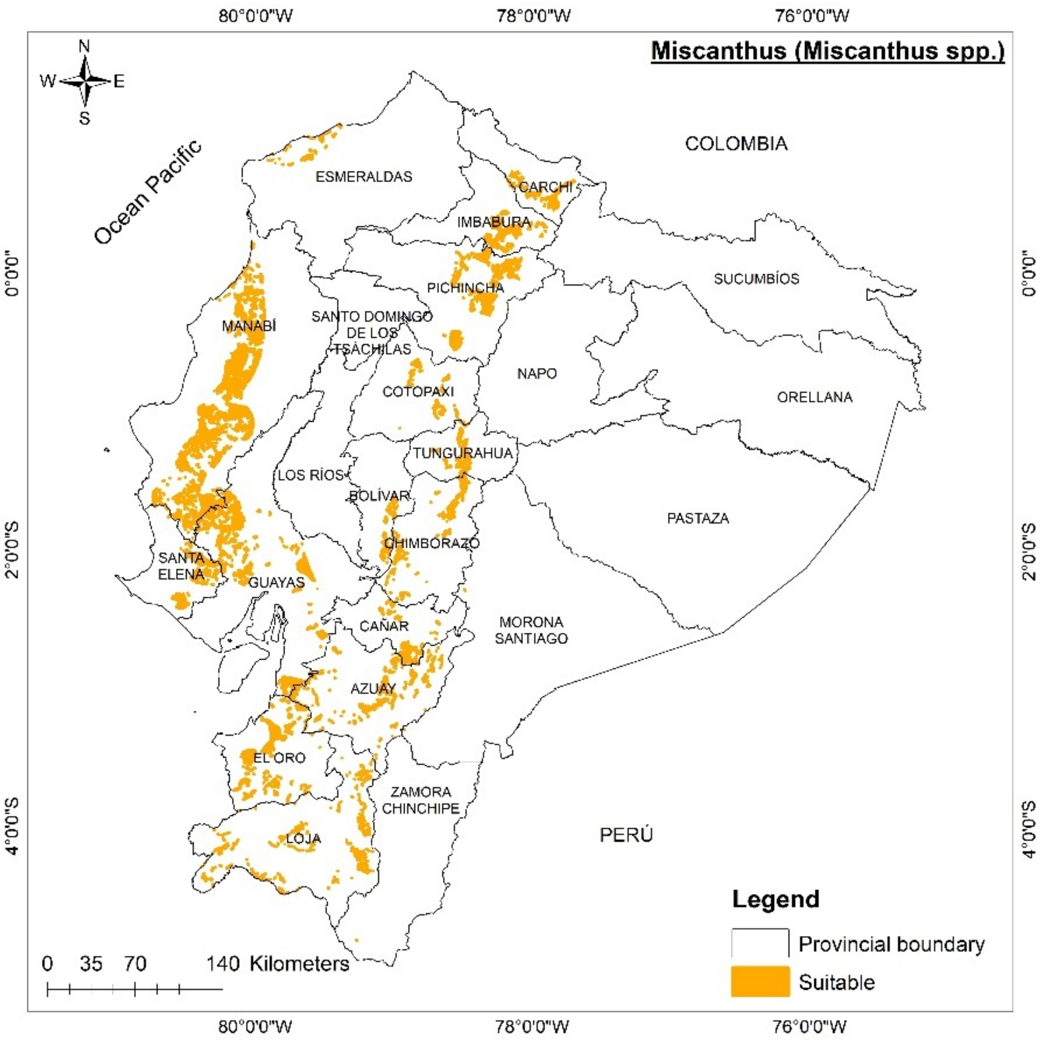

Figure 27. Available surface for Miscanthus production in Ecuador

Results show that Giant reed accounts for the highest optimal area with 85,777.66 ha in total, followed by Miscanthus with 40,090.11 ha. Both crops belong to the Poaceae family, which can be found in the wild, as shown in Figure 28 [305].

Figure 28. Natural occurrence of plants from Arundineae subfamily in Ecuador

4.2.7. Energy yield estimation per crop

As mentioned in methodology Section 3.2.9., four main technological categories were identified of biomass plants, including reference values for size and efficiency: Steam power plants, externally-fired gas turbines, biomass integrated gasification and combined cycle power plants.

Using the information mentioned above, the net potential energy yield per technology with different capacities and efficiencies was estimated. Results are shown in Table 29.

Giant reed ranks first with a potential net energy yield of 4,024,401.74 MWh/year using combined-cycle power plant technology with 90–100 MW installed capacity within the studied energy crops. The highest result is obtained with combined cycle 90–100 MW at 40% upper limit technology.

Table 30. Potential Net Energy yield per technology

Crop	Gross energy potential MWh/year	Potential Net Energy yield per technology (MWh/ year)											
		Steam power plants (backpressure turbines) 20-25 MW		Steam power plants (condensing turbines) 5–50 MW		Externally-fired gas turbines 5–25 MW (simple cycle)		Externally-fired gas turbines 10–30 MW (combined cycle)		Biomass integrated gasification 40–60 MW simple cycle		Combined cycle 90–100 MW combined cycle	
		Lower limit 10%	Upper limit 20%	Lower limit 22%	Upper limit 28%	Lower limit 25%	Upper limit 30%	Lower limit 30%	Upper limit 40%	Lower limit 21%	Upper limit 25%	Lower limit 35%	Upper limit 40%
Bamboo	2,677,144	267,714	535,429	588,972	749,600	669,286	803,143	803,143	1,070,858	562,200	669,286	937,001	1,070,858
Hemp	1,618,783	161,878	323,757	356,132	453,259	404,696	485,635	485,635	647,513	339,944	404,696	566,574	647,513
Eucalyptus	4,350,559	435,056	870,112	957,123	1,218,156	1,087,640	1,305,168	1,305,168	1,740,223	913,617	1,087,640	1,522,696	1,740,223
Giant reed	10,061,004	1,006,100	2,012,201	2,213,421	2,817,081	2,515,251	3,018,301	3,018,301	4,024,402	2,112,811	2,515,251	3,521,352	4,024,402
Pine	4,090,026	409,003	818,005	899,806	1,145,207	1,022,506	1,227,008	1,227,008	1,636,010	858,905	1,022,506	1,431,509	1,636,010
Miscanthus	5,853,166	585,317	1,170,633	1,287,697	1,638,886	1,463,291	1,755,950	1,755,950	2,341,266	1,229,165	1,463,291	2,048,608	2,341,266
Total	28,650,681	2,865,068	5,730,136	6,303,150	8,022,191	7,162,670	8,595,204	8,595,204	11,460,273	6,016,643	7,162,670	10,027,739	11,460,273

4.2.8. Energy yield estimation per province

To determine the energy potential per province, a crop map overlay was conducted to determine the intersection areas where two or more crops share the same surface. The total and intersection areas are shown in supplementary material Annex 2. Figure 29 illustrates the intersection of crops identified.

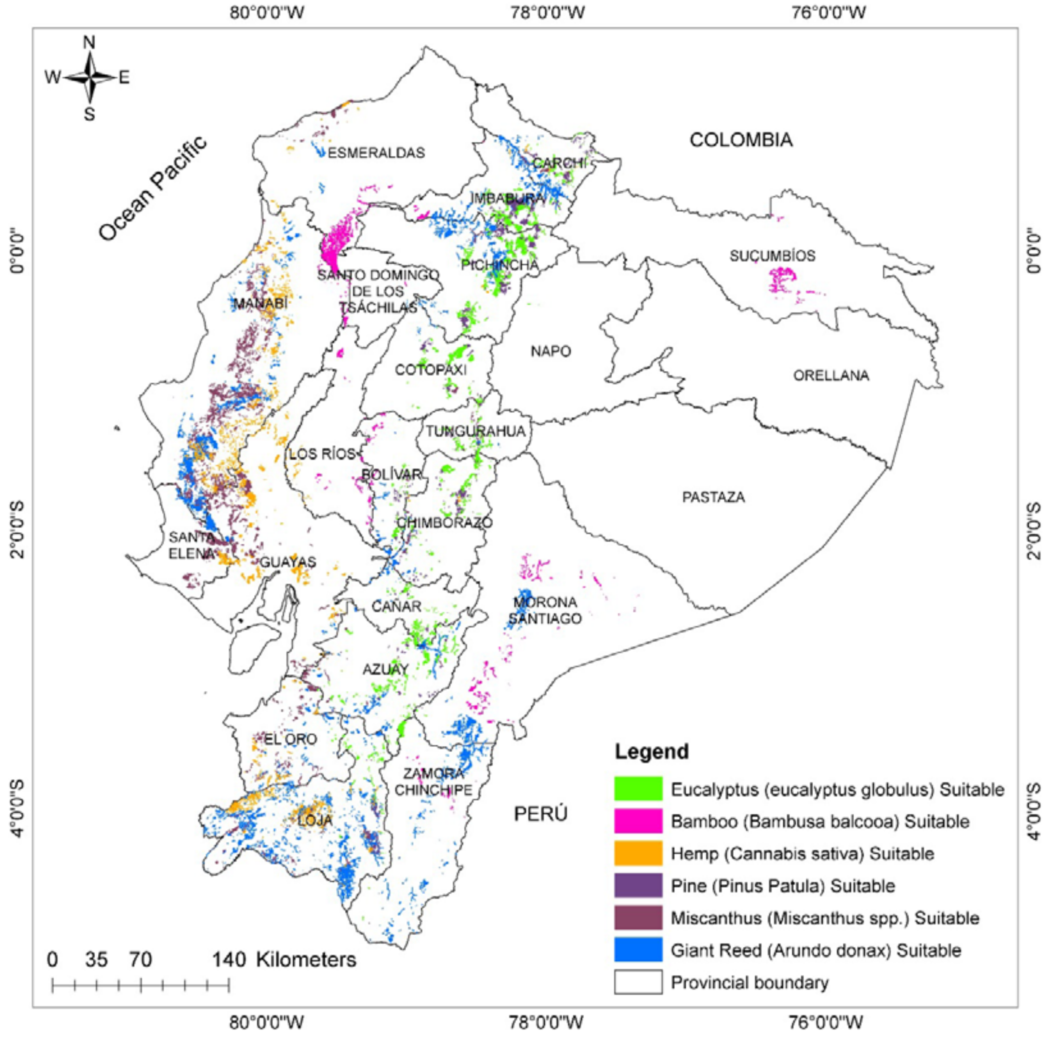

Figure 29. The intersection of resulting areas for the selected biomass crops

Crops with the highest energy yield per hectare per year were prioritized over the rest crops if sharing the same area. E.g., if the area was shared by giant reed, Miscanthus, and eucalyptus, giant reed was prioritized since it has the highest energy yield according to Table 30, in this regard the area was maintained for giant reed and subtracted for the rest of crops. The total overlapped areas per province are shown in Annex 2.

Finally, the resulting number of hectares was multiplied by the potential energy yield per crop per year and determined the net energy yield per technology; the methodology is described in Section 3.2.9. Table 31 shows the results per province and technology.

Results show that combined cycle power plant technology presents the highest energy yield at its upper levels. In terms of electricity production, results show that a total of 9,134 GWh could be produced in the identified area. It was observed that although Amazonian provinces are large, Orellana and Pastaza provinces account for 0 identified areas, while in Morona Santiago, Zamora Chinchipe, Sucumbíos, and Napo, an area corresponding to 5%,4%,2%, and 0,01% respectively were identified. This is explained because most of the protected areas are in these regions.

Table 31. Gross energy potential per selected crop

Crop	Gross energy potential (GJ/ha·year)	Sources	Ranking
Giant reed	422.25	[260]	1
Bamboo	407.40	[259]	2
Eucalyptus	396.00	[262] [263]	3
Pine	330.03	[246] [266]	4
Miscanthus	283.34	[252]	5
Hemp	244.40	[251] [249] [249]	6

Table 32. Net energy yield per technology per province

Province	Gross energy potential MWh/year	Energy yield per technology (MWh/year)											
		Steam power plants (backpressure turbines) 20-25 MW		Steam power plants (condensing turbines) 5–50 MW		Externally-fired gas turbines 5–25 MW (simple cycle)		Externally-fired gas turbines 10–30 MW (combined cycle)		Biomass integrated gasification 40–60 MW simple cycle		Combined cycle 90–100 MW	
		Lower limit 10%	Upper limit 20%	Lower limit 22%	Upper limit 28%	Lower limit 25%	Upper limit 30%	Lower limit 30%	Upper limit 40%	Lower limit 21%	Upper limit 25%	Lower limit 35%	Upper limit 40%
Azuay	1,154,316.35	115,431.63	230,863.27	253,949.60	323,208.58	288,579.09	346,294.90	346,294.90	461,726.54	242,406.43	288,579.09	404,010.72	461,726.54
Bolivar	323,404.65	32,340.46	64,680.93	71,149.02	90,553.30	80,851.16	97,021.39	97,021.39	129,361.86	67,914.98	80,851.16	113,191.63	129,361.86
Cañar	296,161.66	29,616.17	59,232.33	65,155.57	82,925.27	74,040.42	88,848.50	88,848.50	118,464.67	62,193.95	74,040.42	103,656.58	118,464.67
Carchi	356,239.73	35,623.97	71,247.95	78,372.74	99,747.12	89,059.93	106,871.92	106,871.92	142,495.89	74,810.34	89,059.93	124,683.90	142,495.89
Chimborazo	686,308.08	68,630.81	137,261.62	150,987.78	192,166.26	171,577.02	205,892.42	205,892.42	274,523.23	144,124.70	171,577.02	240,207.83	274,523.23
Cotopaxi	949,928.31	94,992.83	189,985.66	208,984.23	265,979.93	237,482.08	284,978.49	284,978.49	379,971.32	199,484.94	237,482.08	332,474.91	379,971.32
El Oro	557,048.14	55,704.81	111,409.63	122,550.59	155,973.48	139,262.03	167,114.44	167,114.44	222,819.26	116,980.11	139,262.03	194,966.85	222,819.26
Esmeraldas	1,560,647.34	156,064.73	312,129.47	343,342.41	436,981.25	390,161.83	468,194.20	468,194.20	624,258.94	327,735.94	390,161.83	546,226.57	624,258.94
Guayas	1,988,653.71	198,865.37	397,730.74	437,503.82	556,823.04	497,163.43	596,596.11	596,596.11	795,461.48	417,617.28	497,163.43	696,028.80	795,461.48
Imbabura	1,781,445.27	178,144.53	356,289.05	391,917.96	498,804.67	445,361.32	534,433.58	534,433.58	712,578.11	374,103.51	445,361.32	623,505.84	712,578.11
Loja	3,112,000.67	311,200.07	622,400.13	684,640.15	871,360.19	778,000.17	933,600.20	933,600.20	1,244,800.27	653,520.14	778,000.17	1,089,200.24	1,244,800.27
Los Rios	180,829.86	18,082.99	36,165.97	39,782.57	50,632.36	45,207.46	54,248.96	54,248.96	72,331.94	37,974.27	45,207.46	63,290.45	72,331.94
Manabi	3,810,698.27	381,069.83	762,139.65	838,353.62	1,066,995.52	952,674.57	1,143,209.48	1,143,209.48	1,524,279.31	800,246.64	952,674.57	1,333,744.40	1,524,279.31
Morona Santiago	1,337,225.07	133,722.51	267,445.01	294,189.52	374,423.02	334,306.27	401,167.52	401,167.52	534,890.03	280,817.26	334,306.27	468,028.77	534,890.03
Napo	3,024.08	302.41	604.82	665.30	846.74	756.02	907.22	907.22	1,209.63	635.06	756.02	1,058.43	1,209.63
Orellana	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Province	**Gross energy potential MWh/year**	**Energy yield per technology (MWh/year)**											
		Steam power plants (backpressure turbines) 20-25 MW		**Steam power plants (condensing turbines) 5–50 MW**		**Externally-fired gas turbines 5–25 MW (simple cycle)**		**Externally-fired gas turbines 10–30 MW (combined cycle)**		**Biomass integrated gasification 40–60 MW simple cycle**		**Combined cycle 90–100 MW**	
		Lower limit 10%	**Upper limit 20%**	**Lower limit 22%**	**Upper limit 28%**	**Lower limit 25%**	**Upper limit 30%**	**Lower limit 30%**	**Upper limit 40%**	**Lower limit 21%**	**Upper limit 25%**	**Lower limit 35%**	**Upper limit 40%**
Pastaza	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pichincha	2,395,877.58	239,587.76	479,175.52	527,093.07	670,845.72	598,969.39	718,763.27	718,763.27	958,351.03	503,134.29	598,969.39	838,557.15	958,351.03
Santo Domingo de los Tsachilas	805,280.95	80,528.10	161,056.19	177,161.81	225,478.67	201,320.24	241,584.29	241,584.29	322,112.38	169,109.00	201,320.24	281,848.33	322,112.38
Santa Elena	2,039.27	203.93	407.85	448.64	570.99	509.82	611.78	611.78	815.71	428.25	509.82	713.74	815.71
Tungurahua	41.16	4.12	8.23	9.05	11.52	10.29	12.35	12.35	16.46	8.64	10.29	14.40	16.46
Sucumbios	514,785.84	51,478.58	102,957.17	113,252.88	144,140.03	128,696.46	154,435.75	154,435.75	205,914.34	108,105.03	128,696.46	180,175.04	205,914.34
Zamora Chinchipe	1,028,882.48	102,888.25	205,776.50	226,354.15	288,087.10	257,220.62	308,664.75	308,664.75	411,552.99	216,065.32	257,220.62	360,108.87	411,552.99
Total	22,835,880.97	2,283,588.10	4,567,176.19	5,023,893.81	6,394,046.67	5,708,970.24	6,850,764.29	6,850,764.29	9,134,352.39	4,795,535.00	5,708,970.24	7,992,558.34	9,134,352.39

5. Discussion

5.1. Life Cycle Assessment of Bioenergy in Islands

As mentioned in the introduction, there is increasing interest in the research of non-variable energy sources on islands to reduce their dependency on imported fossil fuels. Some studies have been conducted regarding the use of alternative oleaginous sources for energy generation on islands; nevertheless, most of them have focused on biofuels produced through transesterification processes. Few studies have analyzed the use of alternative energy sources such as WCO in island systems. Moreover, there is a lack of research regarding the environmental impacts of electricity generation from biomass feedstocks in this type of ecosystem.

In this context, this component of the study aimed to evaluate the environmental impact of the direct use of non-transesterified feedstock options for electricity generation on islands—imported RPO vs. locally produced WCO—in addition to providing direct data on the emissions from the combustion of these two materials.

According to the results, straight RPO-based electricity production accounts for a higher environmental footprint when compared to WCO in all impact categories, as presented in Figure 20.

The impact category results presented in Table 21 are coherent in magnitude with similar studies developed for Jatropha curcas based electricity generation [86].

As mentioned, the main strength of this study is the presentation of a full-chain LCA for both feedstocks to provide inputs to decision-makers when analyzing bioenergy options for islands, and the provision of firsthand measurement data from combustion emissions.

In terms of limitations, we must mention that although the selected agricultural production area represents the average production conditions of palm oil in Ecuador, a bigger sample including other producer provinces and other land-use changes could increase the representativeness of the FFB production system in the country.

Regarding emissions testing and electricity generation yield, our results are in good agreement with the literature [174, 203 and 301]. Nevertheless, we observed some contradicting conclusions reported in other studies [302, 303].

In terms of fuel consumption, the results obtained in the experiment for diesel (194.73 g/kWh) are consistent in magnitude with results obtained by Alessandro et al 2016.[179], (255 g/kWh). Moreover, results obtained for RPO (301.93 g/kWh) are consistent with data provide for biodiesel from vegetable oil by the same author (293 g/kWh). It must be mentioned the results obtained in the present study for energy yield per unit of WCO are closer to diesel than RPO and biodiesel.

The results of the present study regarding CO emissions from vegetable oil combustion (2120 ppm) are lower than results obtained by Altin et al. (2001) [309] (4000 ppm). Nevertheless, CO emissions resulting per energy unit (13.48 kg/MWh) are consistent with results obtained by Dhanasekaran et al. (2019) [310] (12.28 kg/MWh).

Concerning CO_2 emissions from vegetable oil combustion from the present study per energy unit (483.85 kg/MWh) are 42% lower than results obtained by Dhanasekaran et al., (2019) [310] (790 kg/MWh).

Nevertheless, emission results from waste cooking oils are difficult to compare because of the different typologies and sources this issue determines a very high variability among results [179].

It is possible to obtain contradicting results in emissions studies because they are dependent on many variables, such as different physical conditions, experimental atmospheres, test equipment, and, especially, the combustion chamber. In this regard, one of the main weaknesses of this study is that the emissions test was performed in a 10 kW–200 rpm engine; this could result in lower efficiency and higher emissions. Besides, it is very difficult to predict the chemical composition of WCO as it is dependent on many factors like temperature, exposure to air, and cooked food composition, among others [311]. These variables can impact the performance of the final material when combusted. Another important limitation of the study is the limited number of emission measurements performed in different conditions than the electricity generation group on Floreana island.

Regarding the LCA data and results, as mentioned, most of the existing studies analyzed transesterified fuels, which made result comparisons difficult as our study relied on straight use. Nevertheless, the calculated environmental burden reduction from WCO usage is still consistent with the literature [175, 232]. According to our results, RPO is the main contributor to GWP with 305 kg CO_2eq, from which around 40% comes from methane CH_4 from wastewater produced during the production of crude palm oil. Palm Oil Mill Effluent (POME) is an underutilized liquid waste stream from palm oil mills which is generated during the palm oil extraction/decanting process and is often seen as a serious environmental issue. Nevertheless, POME could be used as a good biomethane source, which can also be used for energy production. Promising research has addressed the potential of POME to generate biohydrogen and biomethane (or a mixture of these: biohythane) for energy purposes [312]. These alternative POME utilizations could dramatically reduce the GHG footprint during the production phase. The second-largest GHG emission source identified in this study is transporting (marine and road), accounting for 61 kg CO_2eq; it is important to mention that this footprint could be reduced if agricultural production areas are located closer to refining facilities and marine ports.

Moreover, N_2O contributes 42 kg CO_2eq; this GHG is commonly derived from the use of nitrogen-based fertilization and was estimated as a function of applied N, as mentioned. It is important to mention that by-products of palm oil production can also be used for fertilization: the use of 300 kg of empty FFB could be equivalent to 4.8 kg of potassium chloride (KCL), 0.25 kg diammonium hydrogen phosphate (DAP), and 10 g of borate per plant [313].

In the case of WCO, the higher contributor to GWP (91% of the total) is the use of electricity from the Galápagos electricity grid which, as mentioned, is heavily reliant on fossil fuels. This footprint could be reduced if more renewable energy is integrated into the system. The second GHG source is the road and marine transportation.

Regarding RPO-based electricity acidification potential, the main contributor with 1.6 kg SO_2eq is ammonia emissions derived from N fertilizer application during the agricultural production of FFB. Thus, it is important to stress the environmental benefits related to the reduction of chemical nitrogenated fertilization. The second contributor, with 20%, is NO_x emission derived from the use of fossil fuels in transport and energy generation during the production process. Regarding WCO-based electricity, the main source of acidification in this study came from SO_2 and NO_x from the combustion of fossil fuels during electricity generation in the Galápagos grid; these impacts are relevant in sensible ecosystems such as islands. According to Glynn (2018) [314], if CO_2 emissions are not reduced, ocean warming and acidification are projected to drastically reduce or eliminate coral reefs from the Galápagos between the years of 2026 and 2035.

In RPO electricity production, chemical oxygen demand (COD) contributes 62% of the total eutrophication potential (PO_4eq); this process is linked to the high amount of oxidizable pollutants found in the wastewater from the extraction phase. In terms of abiotic depletion (ADP), 56% of the total antimony (Sb) equivalent is attributed to the use of fossil fuels in RPO production, including fuels used for input production and materials.

Impact categories results that are expressed in the same units were compared with results obtained by Munoz et al., 2018 [86]. It must be mentioned that the reference work is an LCA for electricity production using <u>*jatropha curcas.*</u> Hereof, the comparisons are based in terms of magnitude or percentage.

Results of the present study for Ozone depletion expressed in kg CFC–11eq. for RPO (1.6×10^{-5}) is 2 times greater than the reference study (7×10^{-6}). For WCO the result (1.7×10^{-6}) represents 24% of the data showed in the reference study.

On the other hand, results obtained for Global warming potential in kg CO_2 eq. for RPO (450) is 3 times greater than the reference study (123). For WCO the result (20) represents 19% of the data showed in the reference study.

It must be considered that the reference work studies Jatropha harvested from live fences and does not considers the usage of agricultural technological packages, thus, fertilizers, pesticides, among other inputs are avoided. Considering the rich and sensible marine ecosystem of the Galápagos, the main contributor to marine ecotoxicity is wastewater from WCO cleaning with 80.6 1,4 Dichlorobenzene equivalent (1,4–DBeq). In this regard, adequate final disposal of the wastewater in this process is crucial to reducing this environmental impact.

Some of the unanswered questions and future research derived from this study are to (i) study the willingness of business owners to provide WCO in Galápagos or other islands; (ii) conduct emissions testing in conditions similar to those of the electric group located on Floreana Island; (iii) analyze the environmental impacts of WCO disposed of in the sewage system in Galápagos; (iv) determine the impact of the potential energy usage of other by-products not exploited in the production cycle, such as palm kernel residues and sludges from the extraction phase; and (v) analyze the land-use change impact of productive zones with high carbon content, such as the Amazonian region.

5.2. Agroecological zoning of second-generation energy crops

According to the Nationally Determined Contribution (NDC) of Ecuador, the country could reduce its aggregated greenhouse emissions from energy, agriculture, industrial processes and waste sectors by the year 2025 compared with 2008 levels by 9% on an unconditional scenario and 20,9% in a conditional scenario supported with international cooperation [96].

According to Carvajal et al. 2020 [315], considering the electricity demand increment linked to the expected socio-economic development for Ecuador in the period 2017 to 2050, and future climate change scenarios, electricity generation will increase from 65 to 74 TWh/year by 2050, which is up to a threefold increase compared to current levels. The named study indicates that under all scenarios, an expansion of hydropower capacity must be complemented by other baseload generation capacity technologies such as natural gas or other renewables such as biomass and geothermal power to provide both peak and baseload generation in low runoff seasons despite the large installed hydropower capacity. In terms of cumulative GHG emissions for period 2015-2050 scenarios projected 110 Gt CO_2e in dry conditions, 48 Gt CO_2e in wet conditions, and 350 Gt CO_2e under the constrain hydropower policy case and the dry climate scenario.

Furthermore, Ramirez et al. 2020 [79], through modelling the life cycle related impacts of different future electricity mix scenarios, demonstrated that the global warming potential of net electricity generation in Ecuador would increase from 12 to 20 times by 2050 over 2016 levels, mainly because of the expected increment in the demand. Besides, the study remarks about the risks to the energy security of the country, as fossil resources scarcity is expected, and climate change uncertainties may affect hydropower generation.

Moreover, Ramirez et al. 2019 [231], performed a life cycle assessment comparing the current thermoelectric technologies operating in Ecuador, the results have shown that the electricity production from Fuel Oil Steam Power (FO- SP) technology presents the highest contribution in terms of greenhouse gas emissions. This technology is used as baseload in Ecuador.

Thereof a biomass-based electricity production and other non-variable renewable energy technologies could be encouraged to replace this type of fossil fuel-based energy source in Ecuador to mitigate GHG emission reductions from the electricity sector.

In the country, the potential for second-generation bioenergy production has only been addressed for agricultural residues through the bioenergy Atlas of Ecuador [7]. Zoning for renewable energy potential in Ecuador has been developed for variable energy resources as solar [87], wind [88], and both resources [89].

On the other hand, agroecological zoning has been developed mainly for food crops [90,91]. In terms of bioenergy resources in Latin America, zoning studies have focused on crop by-products [92], few studies have focused on dedicated bioenergy crops [27, 93–95].

The potential of producing bioenergy in marginal lands has been addressed in many studies [235, 238, 275 and 309]. Worldwide 1.4 billion hectares have been identified as suitable to be allocated for bioenergy production. In Latin America, there are currently 343 surplus million hectares, which could be dedicated to this end [84].

The methodology applied in this study considers the total exclusion of agricultural production, anthropogenic, and natural importance areas.

The research presents wide ranges when estimating the potential of bioenergy production using marginal lands worldwide, ranging from 30 to 1000 EJ per year at the year 2050 [310, 311]. And 130 to 270 EJ/year when sustainability variables are taken into consideration [319]. The agroecological zoning performed for Ecuador resulted in potential energy production of 9,134 GWh/year. This represents 31% of the electricity demand in 2019, 9.4%, 5.3%, and 5.9% of the three projected electricity generation scenarios for the year 2050 developed by IIGE [320].

Batidziari et al. (2012) [321] recommended critical factors to be considered when addressing biomass potentials. In the following section, these factors are contrasted with the methodology applied in the presented study, the limitations are identified, and recommendations remarked.

a) Biomass demand for food, feed, fibre and biomaterials. As indicated in Section 3.2.7.4, the methodological approach used in this study excluded productive zones dedicated to the main agricultural products from food safety and economic perspectives in the country. Nevertheless, the prioritization of crops can vary according to national development goals. Also, fibre and biomaterials producing crops were not considered as a priority in this research. Thereof, the available area for dedicated bioenergy crops identified in this study could compete with the mentioned possible land uses.

b) Improvements in agricultural and forestry management and technologies. Within this factor, the impact of possible agronomic, forestry management, and efficiency improvements related to food production is recommended to be evaluated. In the current study, this factor was not considered. The increment of yield per agricultural unit due to efficient agricultural practices could reduce the amount of land required for food production, this could imply an increment in the availability of land for bioenergy production. Nevertheless, it must be analyzed the opportunity cost from a sustainability perspective to determine the best land use. It is recommended to incorporate these variables for main agricultural products in future work.

c) Use of marginal and degraded land. The main recommendation within this factor is to use accurate and spatially explicit land-use datasets and digital mapping to identify the location, extend, severity, and availability of land for energy crops. The present study utilizes the mentioned inputs in a top-down approach that evaluates the current land use, excluded human or ecological importance areas, and identifies available land for specific bioenergy crops according to its edaphoclimatic requirements. An alternative bottom-up approach would be identifying areas not suited for traditional agriculture production with low ecological importance that could still be used to produce bioenergy crops. Nevertheless, the approach to be used before starting commercial production must be decided jointly among the stakeholders of the project.

d) Water availability and use. The study considers the water requirements of the recommended bioenergy crops and the availability of precipitation to meet this demand. However, the use of irrigation water could determine an increment of available zones for dedicated bioenergy crops, nevertheless, water distribution among food and energy crops must be carefully studied. In addition, current and future water availability should be considered in further research. Besides, as mentioned in Section 2.1.1, the water footprint for biomass production is a recurring issue. The following aspects could also be integrated into this type of assessments: water availability (current and future) including mapping of water stress, ground and surface water availability and quality, environmental water requirements, agricultural water withdrawal, freshwater runoff, freshwater demand by application, projected climate change impacts (precipitation and evapotranspiration rates); impact of improved water use efficiency; the impact of energy crop choices and management (input of agrochemicals); irrigation impacts (salinization, biodiversity impacts, wetlands); watershed-level assessment of water use impacts [321].

e) Nature protection and expansion of protected areas. As mentioned in Section 3.2.7.4, ecological importance zones were excluded from the zoning. Nonetheless, aspects as the future expansion of natural protected areas, long term climate change impacts, shifts in vegetation zones, and bioenergy induced eutrophication and acidification among other facts most be considered in future studies. The increment on protected areas could reduce the available surface for bioenergy production, In section 3.2.7.4 the present study identified in advance ecological importance zones not considered currently in the national protected areas system which could be included on PANE in the future.

f) Climate change and GHG emissions. The present work does not determine the global warming mitigation potential associated with bioenergy production from the studied crops. This limitation should be addressed in future studies through life cycle assessment or other GHG evaluation methodologies. The scope of the GHG emissions assessment must include the whole supply chain. Other important aspects that should be considered are the direct and indirect land-use change of bioenergy crops and agroclimatic variations due to climate change. In Ecuador, the integration of future climate variability scenarios is crucial for long term biomass production future development due to its high vulnerability. The projection of future climate change scenarios in terms of temperature and precipitation would change the resulting available areas identified in this study. It is important to consider uncertainty levels before providing results considering climate change scenarios.

g) Choice of energy crops. Variables to consider within these criteria are the impact of energy conversion efficiency and higher energy yields between woody and herbaceous plants when compared to grains and oils, avoidance of food-fuel conflicts, as well as inputs requirements. Although most of these criteria were addressed in the present study (Section 3.2.5). It is recommended to analyze further aspects as the comparison of woody and herbaceous with grains and oils and inputs requirements. The bioenergy potential of non-edible vs edible crops is an important issue to be addressed before desition making. The present study does not consider the potential of edible bioenergy crops. Regarding land competition, edible crops as grains and oils are more demandant in terms of soil, water and agricultural inputs. It is recommended to address the land competition issue between theses types of bioenergy crops in future works to identify potential overlaps. One of the limitations of this study is that production yields correspond to literature values. Therein, agricultural experimentation and yield evaluation under Ecuadorian conditions in the recommended areas is crucial before starting commercial production of any feedstock presented in this study. Research data obtained by pilot projects in the identified areas could provide accurate national yield information.

h) Use of agricultural and forestry by-products: Within this critical factor, the changes in residue/waste generation, and its potential future applications must be addressed. This fact is a limitation in the present study that should be developed and included in future work. The increase in the production of agricultural and forestry by-products with energy ends could not influence the production of dedicated bioenergy crops, but to complement the final bioenergy share in the country to satisfy the incremental demand projected.

i) Economic parameters. Including economic factors as market mechanisms and value chain associated cost of biomass production. These aspects were not included in the evaluation as the present study aimed to explore the potential for bioenergy dedicated crops from an agronomical perspective. Nevertheless, these important variables should be considered in cost-benefit decision-making analysis when this information is available for Ecuador.

Future technology improvements and more efficient technological routes could increase the overall efficiency of the transformation process increasing energy yields.

Moreover, it is important and recommended to consider a holistic approach such as life cycle sustainability assessment (LCSA) to evaluate the environmental, social and economic impacts to support decision-making processes towards bioenergy feedstock selection.

On the other hand, the combination of bioenergy with carbon capture and storage mechanisms (BECCS) has been identified as a potential negative emissions technology. Nevertheless, despite its hypothetical advantages, BECCS presents challenges as: land competition for food production, CO_2 emissions associated with biomass cultivation, water usage, harvesting and processing among other factors that could reduce the ability of BECCS to result in a net removal of CO_2 from the atmosphere [144] [124]. The implementation of BECCS using the results of this study could represent a promising way to support the achievement of Ecuador's NDC's goals, though, its implications must be addressed from a sustainable approach.

Finally, as mentioned, the current study utilizes geographical information produced by governmental entities; variables studied, and scales can change over time; in this regard, it is important to recommend using updated GIS material when commercial production decisions are considered.

The only bioenergy sources currently considered in the energy prospective scenarios for Ecuador are bagasse and firewood. It is recommended to consider integrating the energy potential of dedicated bioenergy crops, as described in this study when energy prospective scenarios are developed for Ecuador.

6. Conclusion

6.1. Life Cycle Assessment of Bioenergy in Islands

The results of this study indicate that a system based on locally generated waste such as WCO is a superior alternative to continental RPO in environmental terms. This is mostly associated with the fact that WCO is a waste material which does not have environmental or resource impacts associated with its production and processing. The life cycle of RPO includes agricultural production, industrial processing, and transport. Besides, fewer resources are used in the in situ processing and transport of WCO compared to RPO.

Both feedstocks, RPO and WCO, independent of their production impacts, meet the conditions for being used as an energy source for non-variable electricity generation on islands. The experience of Galápagos with the direct use of vegetable oils provides valid evidence for the use of non-transesterified oleaginous feedstocks for electricity generation which can be extrapolated to other islands.

Nevertheless, further analysis should be performed to understand the flows and the current and future availability of WCO on an island that considers this as an option. It is also important to study in more detail the impacts of incorrect WCO disposal in fragile ecosystems such as islands.

Regarding RPO, it is important to include impacts related to land-use change in agricultural productive zones where deforestation is an issue.

Finally, the electricity production test shows that WCO has higher electricity yield when compared to RPO. This can be associated with the partial hydrogenation that oils suffer during the cooking process due to their contact with water at high temperatures.

6.2. Agroecological zoning of second-generation energy crops

Results shown in this study demonstrated the availability of producing bioenergy dedicated crops in marginal lands of Ecuador.

In terms of energy yield per hectare, giant reed occupies the first place with an energy potential yield of 422.25 Gj/ha per year followed by bamboo which is currently produced in Ecuador as a construction material. It must be mentioned that both species are considered within the non-woody species

On the other hand, in the woody biomass eucalyptus presents the higher energy yield with 396 GJ/ha per year.

In terms of land availability for agricultural production, giant reed also presents the greatest potential with 38 % of the total resulting areas.

It must be taken into account that higher efficiency demands larger installed capacities [315, 316]. For this reason, it is important to implement large scale production sites. These sites could emulate the logistics of sugar cane production systems as the best performers (Miscanthus, giant reed and bamboo) belong to the same family Poaceae and share some physiological characteristics with sugar cane.

7. Future Work

To provide a robust framework for fostering bioenergy production in Ecuador and the Latin American region, the results presented in this thesis must be improved, complemented, and extrapolated. Besides, new questions, hypothesis, and scenarios should arise from this work to increase the scientific bases for bioenergy decision making. Thereof, the following ideas and research niches for future work are presented.

For the Life Cycle Assessment study, it is important to compare the electricity production performance of different vegetable oils in different engines configurations. The "willingness to sell" of waste cooking oil from large vegetable oil consumers must be addressed in Galapagos or any other island before the implementation of a pilot project. It is important to develop national LCI databases to be adopted in future studies.

Future work must also consider determining the lipidic profile of the fatty acids present in waste cooking oils from a defined region to be studied, these results can help to identify and forecast the energy performance of waste cooking oil. The last suggested study could be complemented with the application of artificial neuronal networks to forecast energy output, emissions, among other parameters.

In the Agroecological Zoning study, it is recommended the implementation of research considering agricultural experimental designs for each of the varieties studied in the geographic areas identified, the yield data of these studies must be used to estimate more accurate energy yields. Furthermore, the methodology provided in this study could be applied to determine the bioenergy potential of local and/or native species. Regarding BECCS, the available capacity of carbon storage and accessible carbon capture technologies in Ecuador must be addressed in future research and complemented with the CO_2 mitigation potential of the results obtained in the present research. The comparison of energy potential between woody and herbaceous plants when compared to grains and oils for bioenergy production must be addressed. Finally, it is important to implement a full chain LCA for the bioenergy production described in this section and perform a comparison with reference fossil fuels.

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9. Annexes

9.1. Annex 1. Zoning exclusions

1. Excluded food safety crops:

   Abacá, Avocado, Chili Pepper, Garlic, Alfalfa, Cotton, Amaranth, Rice, Pea, Oats, Forage Oats, Banana, Broccoli, Cocoa, Coffee, Sweet Potato, Artisan Sugar Cane, Industrial Sugar Cane, Barley, White Onion, Red Onion , Pearl Onion, Rye, Cherimoya, Chocho, Cabbage, Peach, Bean, Strawberry, Granadilla, Soursop, Guava, Broad bean, Lettuce, Lemon, Corn, Tangerine, Mango, Peanut, Passionfruit, Melloco, Melon, Blackberry, Orange, Naranjilla, Oca, Orito, African Palm, Palmito, Potato, Papaya, Gherkin, Pepper, Pineapple, Pitahaya, Banana, Quinoa, Watermelon, Soy, Tobacco, Tea, Tree Tomato, Kidney Tomato, Wheat, Grape, Uvilla, Vanita, Yucca, Yellow Carrot, White Carrot, Pumpkin.

2. PANE - National Heritage Areas:

   Reserva Ecológica Antisana, Reserva Ecológica Arenillas, Parque Nacional Cajas, Parque Nacional Cayambe Coca, Reserva Biológica Cerro Plateado, Reserva de Producción de Fauna Chimborazo, Reserva Ecológica Cof1n Bermejo, Reserva Ecológica Cotacachi Cayapas, Parque Nacional Cotopaxi, Reserva de Producción de Fauna Cuyabeno, Reserva Ecol1gica El 1ngel, Área Nacional de Recreación El Boliche, Reserva Biol1gica El Cóndor, Refugio de Vida Silvestre El Pambilar, Reserva Biológica El Quimi, Refugio de Vida Silvestre El Zarza, Reserva Marina Galera San Francisco, Refugio de Vida Silvestre Isla Santa Clara, Área Nacional de Recreación Isla Santay, Refugio de Vida Silvestre Islas Corazón y Fragatas, Refugio de Vida Silvestre La Chiquita, Reserva Biológica Limoncocha, Parque Nacional LLanganates, Reserva Ecológica Los Ilinizas, Área Nacional de Recreación Los Samanes, Parque Nacional Machalilla, Reserva Ecológica Mache Chindul, Reserva Ecológica Manglares Cayapas

Mataje, Reserva Ecológica Manglares Churute, Refugio de Vida Silvestre Manglares El Morro, Reserva de Producción Manglares El Salado, Refugio de Vida Silvestre Manglares Estuario del Río Muisne, Refugio de Vida Silvestre Manglares Estuario del Río Esmeraldas, Refugio de Vida Silvestre Pacoche, Área Nacional de Recreación Parque Lago, Refugio de Vida Silvestre Pasochoa, Parque Nacional Podocarpus, Reserva Geobotinica Pululahua, Reserva de Producción de Fauna Puntilla de Santa Elena, Parque Nacional Sangay, Parque Nacional Sumaco Napo-Galeras, Parque Nacional Yacuri, Parque Nacional Yasuní.

3. Anthropic areas excluded in zoning:
   Area in Process of Urbanization, Populated Area, Discharge Bypass, Pipeline Bypass, Research Camp, Canal, Quarry, Cemetery, Collection Center, Populated Center, Airport Complex, Archaeological Complex, Commercial Complex, Communications Complex, Rastro Complex , Health Complex, Educational Complex, Photovoltaic Complex, Hydroelectric Complex, Industrial Complex, Military Complex, Penitentiary Complex, Port Complex, Recreational Complex, Religious Complex, Thermoelectric Complex, Stable, Pumping Station, Toll Station, Gas Station, Poultry Farm, Pig Farm, Racecourse, Anthropic Infrastructure, Mine, Pillager, Oxidation Pool, Landing Strip, Composting Plant, Drinking Water Treatment Plant, Stone Aggregate Crushing Plant, Agricultural Plaza, Livestock Plaza, Poza, Road Network, Landfill Sanitary, Salinera, Silo, No Information, Electrical Substation, Urban, Garbage Dump, Nursery, P Zone Esaje, Oil Blocks.

4. Areas of water sources:
   The excluded water sources are: Artificial Water Body, Natural Water Body, Sewage Deposit, Unknown, Reservoir, Packing Plant, Swamp or Swamp, Lava Flow, Glacier, Lake / Lagoon, Snow & Ice, Double River.

5. Areas classified as miscellaneous:

   The excluded zones considered as Miscellaneous are: Rocky Outcrop, Flood Area, Erosion Process Area, Eroded Area, Saline Area, Sandbank, Wasteland.

9.2. Annex 2. Zoning intersected areas

Table 33. Zoning crops intersections per province

PROVINCE CROP	AREA (ha)
AZUAY Eucalipto	495.06
AZUAY Pino	497.87
AZUAY Pino Eucalipto	1,890.09
AZUAY Cañamo	116.81
AZUAY Cañamo Eucalipto	58.52
AZUAY Carrizo	3294.28
AZUAY Carrizo Pino	16.07
AZUAY Carrizo Cañamo	90.98
AZUAY Miscanthus	763.07
AZUAY Miscanthus Eucalipto	700.49
AZUAY Miscanthus Pino	254.77
AZUAY Miscanthus Pino Eucalipto	2020.23
AZUAY Miscanthus Cañamo	16.93
AZUAY Miscanthus Cañamo Pino Eucalipto	5.69
AZUAY Miscanthus Carrizo	253.03
AZUAY Miscanthus Carrizo Eucalipto	101.56
AZUAY Miscanthus Carrizo Pino	28.79
AZUAY Miscanthus Carrizo Pino Eucalipto	26.09
AZUAY Miscanthus Carrizo Cañamo	2.66
BOLÍVAR Eucalipto	337.99
BOLÍVAR Pino	240.30
BOLÍVAR Pino Eucalipto	129.27

PROVINCE	CROP	AREA (ha)
BOLÍVAR	Bamboo	926.46
BOLÍVAR	Cañamo	10.70
BOLÍVAR	Carrizo	554.37
BOLÍVAR	Miscanthus	65.19
BOLÍVAR	Miscanthus Eucalipto	59.11
BOLÍVAR	Miscanthus Pino	311.23
BOLÍVAR	Miscanthus Pino Eucalipto	329.90
BOLÍVAR	Miscanthus Carrizo	44.74
CAÑAR	Eucalipto	219.60
CAÑAR	Pino	93.72
CAÑAR	Pino Eucalipto	301.40
CAÑAR	Carrizo	967.78
CAÑAR	Carrizo Eucalipto	14.36
CAÑAR	Miscanthus	13.65
CAÑAR	Miscanthus Eucalipto	110.05
CAÑAR	Miscanthus Pino	48.47
CAÑAR	Miscanthus Pino Eucalipto	885.18
CAÑAR	Miscanthus Cañamo Pino Eucalipto	0.01
CAÑAR	Miscanthus Carrizo Eucalipto	0.02
CAÑAR	Miscanthus Carrizo Pino Eucalipto	0.58
CARCHI	Eucalipto	109.65
CARCHI	Pino	342.56
CARCHI	Pino Eucalipto	216.30
CARCHI	Cañamo	96.24
CARCHI	Cañamo Eucalipto	0.39
CARCHI	Carrizo	1187.95

PROVINCE CROP	AREA (ha)
CARCHI Carrizo Cañamo	8.34
CARCHI Carrizo Cañamo Eucalipto	0.91
CARCHI Miscanthus	248.70
CARCHI Miscanthus Eucalipto	112.94
CARCHI Miscanthus Pino	570.73
CARCHI Miscanthus Pino Eucalipto	119.25
CARCHI Miscanthus Cañamo Eucalipto	10.25
CARCHI Miscanthus Cañamo Pino Eucalipto	74.15
CARCHI Miscanthus Carrizo	259.07
CARCHI Miscanthus Carrizo Eucalipto	2.55
CARCHI Miscanthus Carrizo Pino	7.96
CARCHI Miscanthus Carrizo Cañamo	29.58
CARCHI Miscanthus Carrizo Cañamo Pino	0.05
CARCHI Miscanthus Carrizo Cañamo Pino Eucalipto	1.39
CHIMBORAZO Eucalipto	868.05
CHIMBORAZO Pino	1082.87
CHIMBORAZO Pino Eucalipto	835.86
CHIMBORAZO Cañamo	195.06
CHIMBORAZO Carrizo	891.19
CHIMBORAZO Miscanthus	298.18
CHIMBORAZO Miscanthus Eucalipto	403.89
CHIMBORAZO Miscanthus Pino	597.97
CHIMBORAZO Miscanthus Pino Eucalipto	1126.33
CHIMBORAZO Miscanthus Cañamo Pino Eucalipto	111.50
CHIMBORAZO Miscanthus Carrizo	111.13

PROVINCE CROP	**AREA (ha)**
CHIMBORAZO Miscanthus Carrizo Eucalipto	38.28
CHIMBORAZO Miscanthus Carrizo Pino	36.53
CHIMBORAZO Miscanthus Carrizo Pino Eucalipto	9.49
CHIMBORAZO Miscanthus Carrizo Cañamo Pino Eucalipto	0.31
COTOPAXI Eucalipto	1508.68
COTOPAXI Pino	1658.92
COTOPAXI Pino Eucalipto	3532.51
COTOPAXI Carrizo	103.87
COTOPAXI Miscanthus	782.28
COTOPAXI Miscanthus Eucalipto	838.17
COTOPAXI Miscanthus Pino	166.22
COTOPAXI Miscanthus Pino Eucalipto	280.82
COTOPAXI Miscanthus Cañamo Eucalipto	130.89
COTOPAXI Miscanthus Cañamo Pino Eucalipto	149.24
EL ORO Eucalipto	47.94
EL ORO Pino Eucalipto	98.37
EL ORO Cañamo	550.01
EL ORO Carrizo	1902.21
EL ORO Carrizo Cañamo	162.08
EL ORO Miscanthus	2434.49
EL ORO Miscanthus Eucalipto	17.75
EL ORO Miscanthus Pino	31.88
EL ORO Miscanthus Pino Eucalipto	33.23
EL ORO Miscanthus Cañamo	261.20
EL ORO Miscanthus Carrizo	279.26

PROVINCE CROP	AREA (ha)
EL ORO Miscanthus Carrizo Eucalipto	12.93
EL ORO Miscanthus Carrizo Pino	5.00
EL ORO Miscanthus Carrizo Cañamo	30.26
ESMERALDAS Bamboo	6324.53
ESMERALDAS Cañamo	906.78
ESMERALDAS Carrizo	1219.76
ESMERALDAS Miscanthus	2114.97
GUAYAS Cañamo	9811.93
GUAYAS Carrizo	2382.60
GUAYAS Carrizo Cañamo	3.14
GUAYAS Miscanthus	11729.63
GUAYAS Miscanthus Cañamo	1218.32
GUAYAS Miscanthus Carrizo	200.74
IMBABURA Eucalipto	938.98
IMBABURA Pino	2016.51
IMBABURA Pino Eucalipto	566.16
IMBABURA Bamboo	1160.66
IMBABURA Cañamo	1.07
IMBABURA Cañamo Eucalipto	18.60
IMBABURA Carrizo	4961.24
IMBABURA Carrizo Eucalipto	75.32
IMBABURA Carrizo Pino	7.02
IMBABURA Carrizo Cañamo	37.50
IMBABURA Carrizo Cañamo Eucalipto	22.91
IMBABURA Miscanthus	57.09
IMBABURA Miscanthus Eucalipto	484.55

PROVINCE CROP	AREA (ha)
IMBABURA Miscanthus Pino	3452.82
IMBABURA Miscanthus Pino Eucalipto	2531.18
IMBABURA Miscanthus Cañamo Eucalipto	22.16
IMBABURA Miscanthus Cañamo Pino	0.60
IMBABURA Miscanthus Cañamo Pino Eucalipto	11.60
IMBABURA Miscanthus Carrizo	120.55
IMBABURA Miscanthus Carrizo Eucalipto	3.91
IMBABURA Miscanthus Carrizo Pino	138.07
IMBABURA Miscanthus Carrizo Pino Eucalipto	115.73
IMBABURA Miscanthus Carrizo Cañamo Pino Eucalipto	3.68
LOJA Eucalipto	428.62
LOJA Pino Eucalipto	254.37
LOJA Cañamo	13.61
LOJA Carrizo	20207.84
LOJA Carrizo Eucalipto	38.39
LOJA Carrizo Pino Eucalipto	3.25
LOJA Carrizo Cañamo	2458.15
LOJA Carrizo Cañamo Eucalipto	33.00
LOJA Miscanthus	156.09
LOJA Miscanthus Eucalipto	30.60
LOJA Miscanthus Pino	2.93
LOJA Miscanthus Pino Eucalipto	334.13
LOJA Miscanthus Cañamo Pino Eucalipto	14.39
LOJA Miscanthus Carrizo	1984.05
LOJA Miscanthus Carrizo Eucalipto	0.01

PROVINCE CROP	AREA (ha)
LOJA Miscanthus Carrizo Pino	381.47
LOJA Miscanthus Carrizo Pino Eucalipto	18.99
LOJA Miscanthus Carrizo Cañamo	47.38
LOJA Miscanthus Carrizo Cañamo Pino	68.05
LOJA Miscanthus Carrizo Cañamo Pino Eucalipto	55.71
LOS RÍOS Bamboo	1442.55
LOS RÍOS Cañamo	171.25
LOS RÍOS Carrizo	26.74
MANABÍ Bamboo	331.62
MANABÍ Cañamo	4099.44
MANABÍ Carrizo	17063.37
MANABÍ Carrizo Cañamo	328.22
MANABÍ Miscanthus	13194.41
MANABÍ Miscanthus Cañamo	908.47
MANABÍ Miscanthus Carrizo	2573.03
MANABÍ Miscanthus Carrizo Cañamo	113.81
MORONA SANTIAGO Eucalipto	31.26
MORONA SANTIAGO Pino	1.26
MORONA SANTIAGO Bamboo	3968.90
MORONA SANTIAGO Carrizo	7526.17
MORONA SANTIAGO Miscanthus Eucalipto	16.06
NAPO Eucalipto	27.49
PICHINCHA Eucalipto	1763.61
PICHINCHA Pino	2560.59
PICHINCHA Pino Eucalipto	1628.16
PICHINCHA Bamboo	4.23

PROVINCE CROP	AREA (ha)
PICHINCHA Cañamo	77.95
PICHINCHA Cañamo Eucalipto	1.74
PICHINCHA Carrizo	5672.59
PICHINCHA Carrizo Eucalipto	73.84
PICHINCHA Carrizo Cañamo	36.18
PICHINCHA Miscanthus	203.59
PICHINCHA Miscanthus Eucalipto	937.92
PICHINCHA Miscanthus Pino	2468.07
PICHINCHA Miscanthus Pino Eucalipto	5988.56
PICHINCHA Miscanthus Cañamo Pino Eucalipto	26.21
PICHINCHA Miscanthus Carrizo	61.24
PICHINCHA Miscanthus Carrizo Eucalipto	85.30
PICHINCHA Miscanthus Carrizo Pino	373.75
PICHINCHA Miscanthus Carrizo Pino Eucalipto	299.11
SANTA ELENA Cañamo	544.17
SANTA ELENA Carrizo	1044.90
SANTA ELENA Miscanthus	5439.30
SANTA ELENA Miscanthus Carrizo	58.33
SANTO DOMINGO DE LOS TSÁCHILAS Bamboo	5995.31
SANTO DOMINGO DE LOS TSÁCHILAS Carrizo	17.39
SUCUMBÍOS Bamboo	2832.70
SUCUMBÍOS Carrizo	0.35
TUNGURAHUA Eucalipto	517.48
TUNGURAHUA Pino	441.28
TUNGURAHUA Pino Eucalipto	178.22
TUNGURAHUA Carrizo	73.57

PROVINCE CROP	AREA (ha)
TUNGURAHUA Carrizo Eucalipto	21.87
TUNGURAHUA Miscanthus	184.30
TUNGURAHUA Miscanthus Eucalipto	129.16
TUNGURAHUA Miscanthus Pino	35.72
TUNGURAHUA Miscanthus Pino Eucalipto	261.48
TUNGURAHUA Miscanthus Cañamo Eucalipto	0.11
TUNGURAHUA Miscanthus Carrizo Eucalipto	21.91
TUNGURAHUA Miscanthus Carrizo Pino Eucalipto	23.11
ZAMORA CHINCHIPE Eucalipto	916.47
ZAMORA CHINCHIPE Pino Eucalipto	2183.14
ZAMORA CHINCHIPE Bamboo	669.67
ZAMORA CHINCHIPE Carrizo	5183.94
ZAMORA CHINCHIPE Carrizo Eucalipto	34.86
ZAMORA CHINCHIPE Miscanthus	0.24
TOTAL AREA (ha)	**221,407.93**

9.3. Annex 3. Maps used in the agroecological zoning

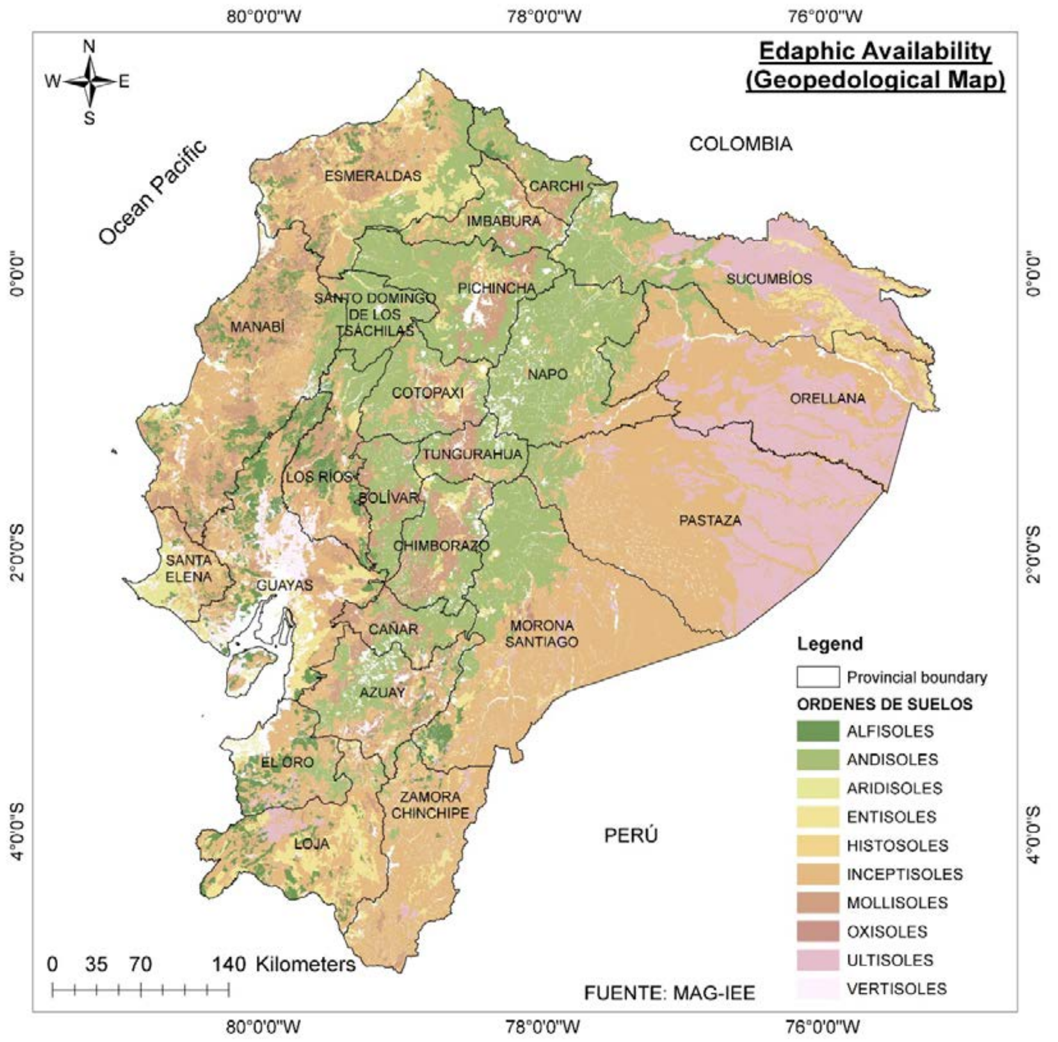

Figure 30. Soil type map

Source: MAG (2020)

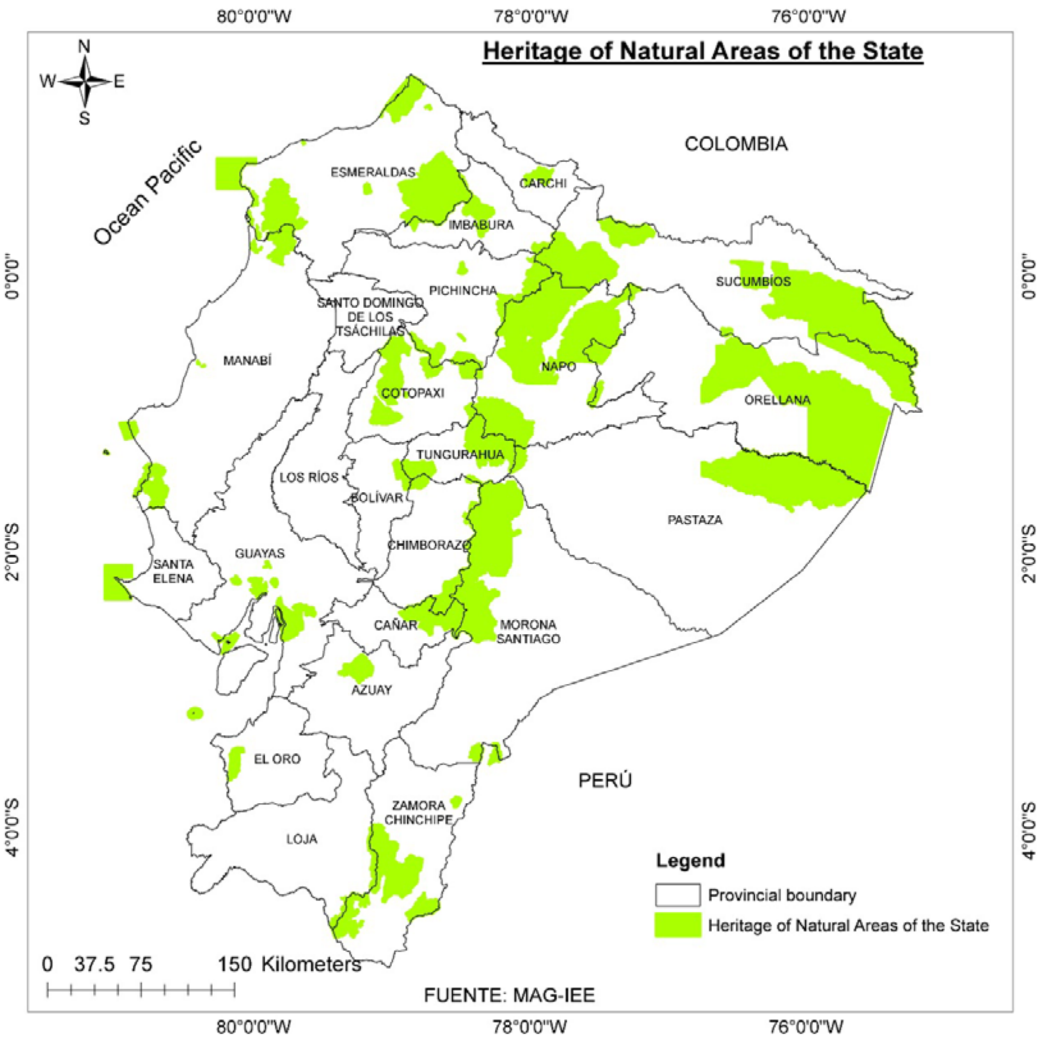

Figure 31. Heritage natural areas of Ecuador

Source: MAG (2020)

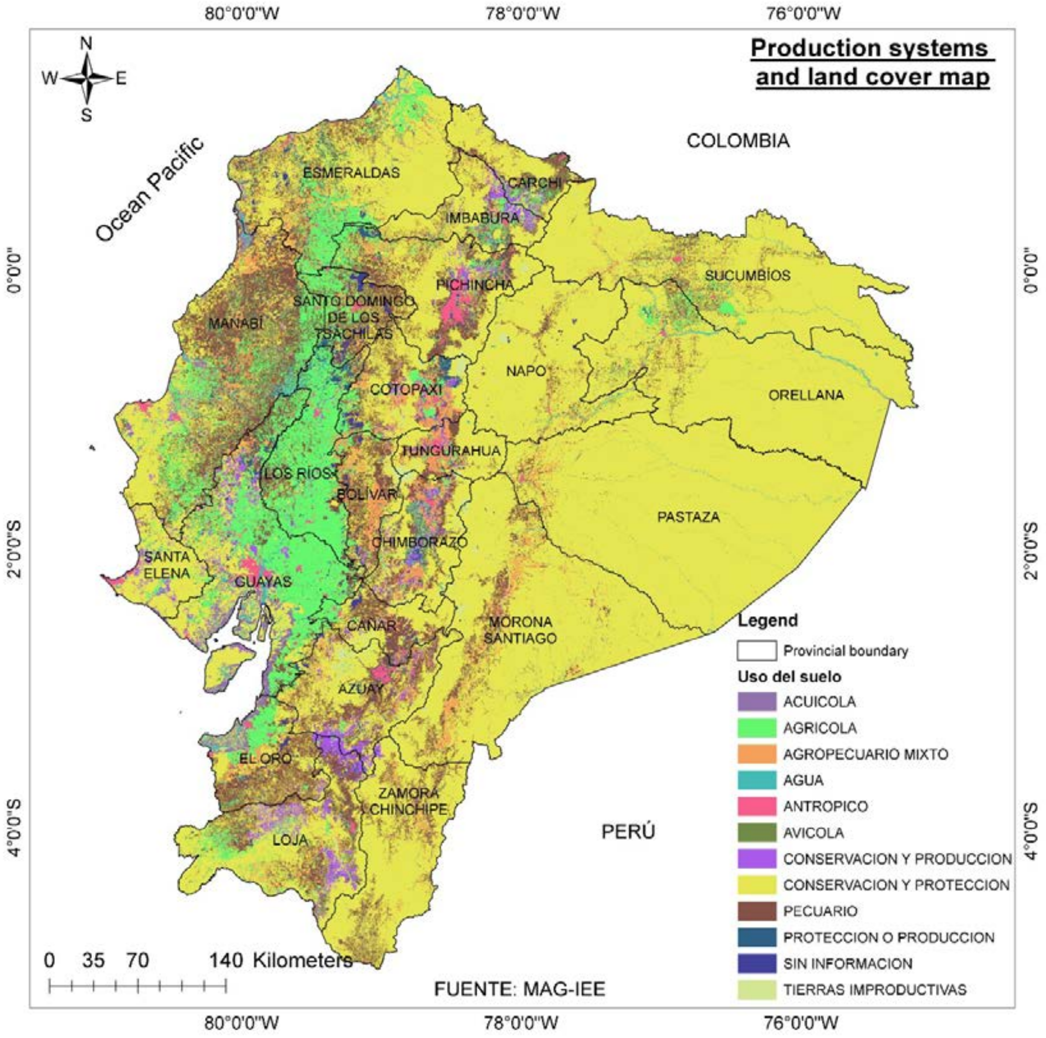

Figure 32. Land use map

Source: MAG (2020)

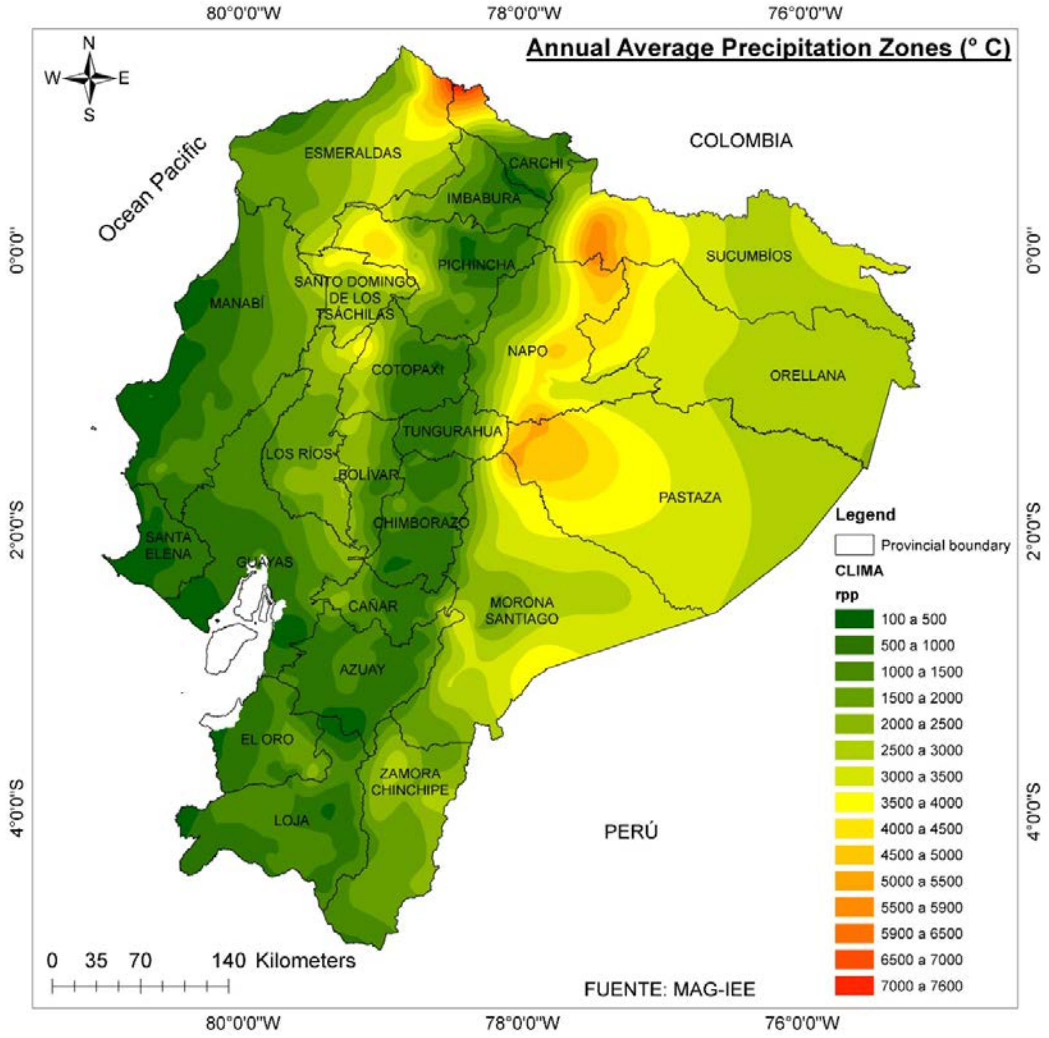

Figure 33. Precipitation map

Source: MAG (2020)

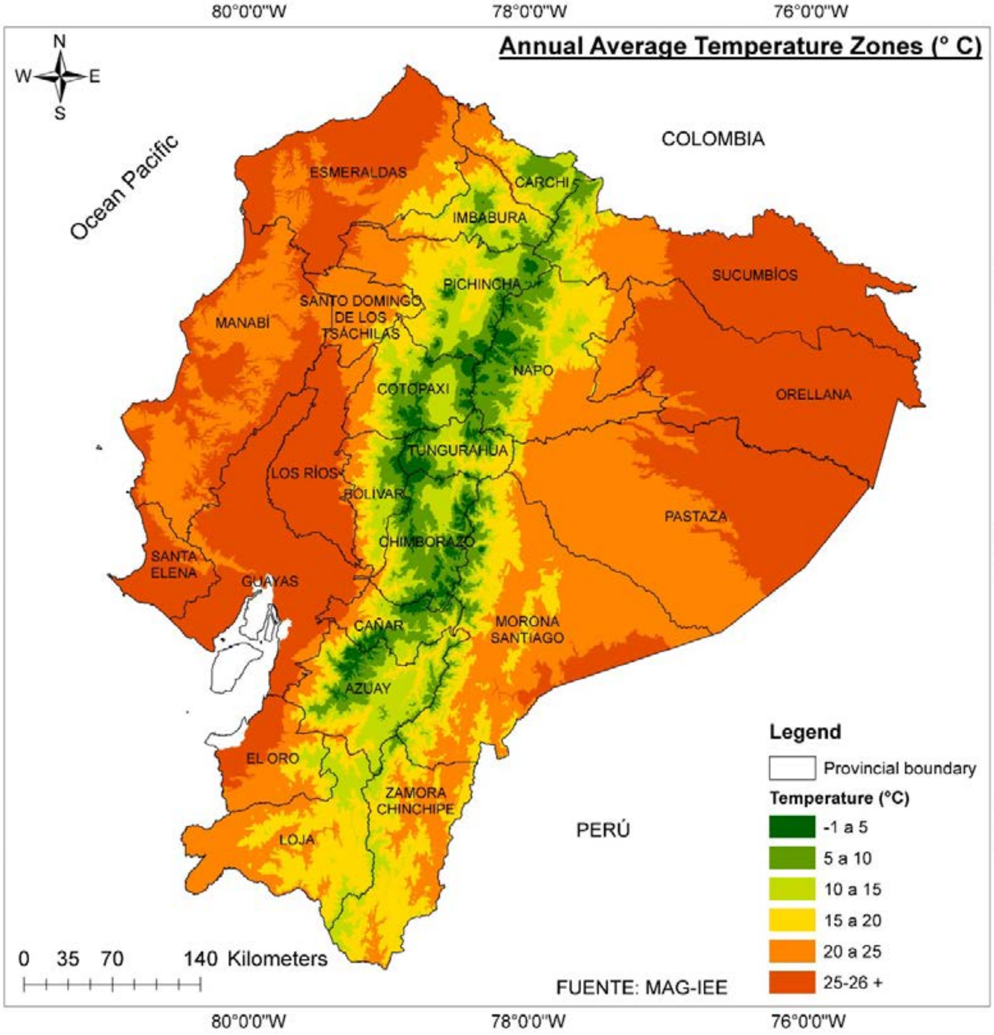

Figure 34. Temperature Zones Map

Source: MAG (2020)

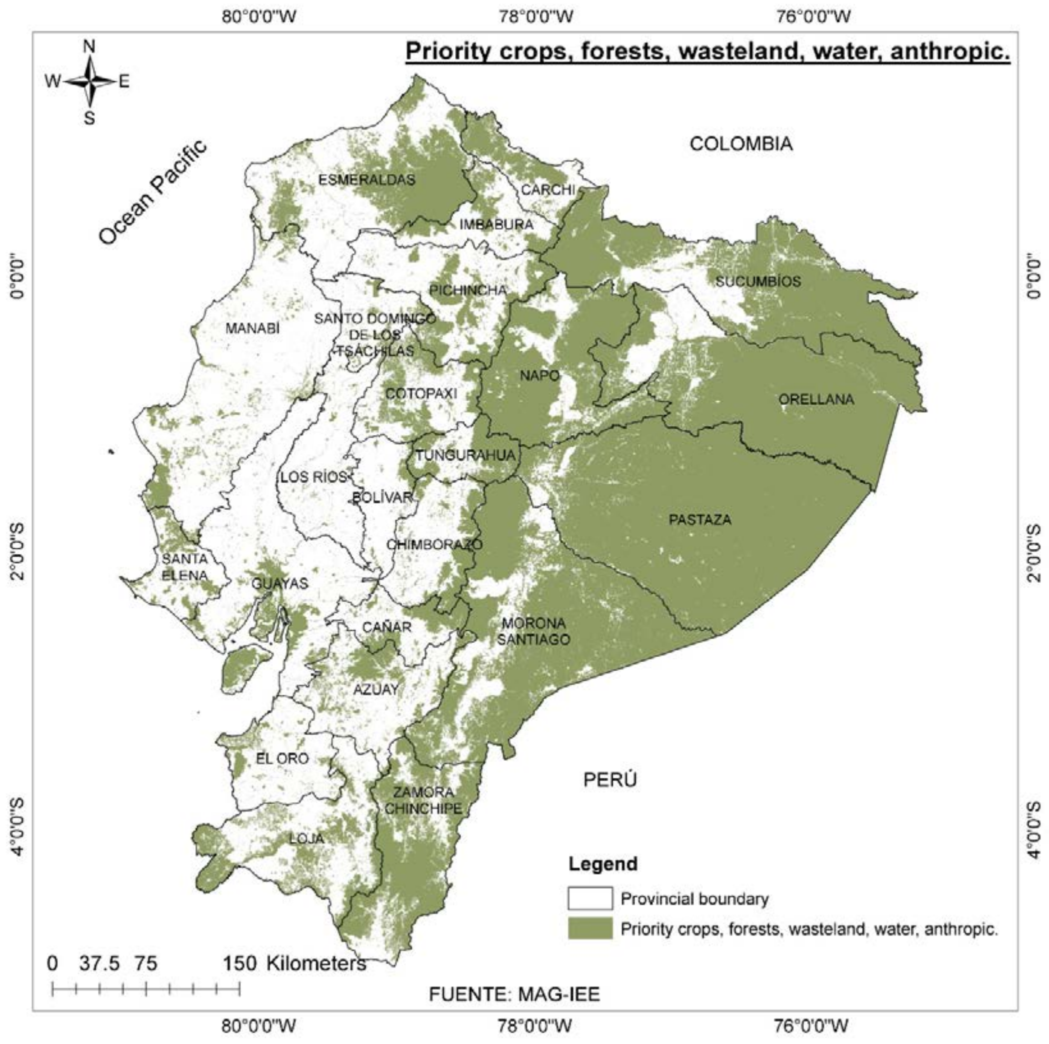

Figure 35. Excluded zones map

Source: MAG (2020)

9.4. Annex 4. Emissions measurement results compilation.

Table 34. Experimental emissions measurement results

Fuel	Sample	Exhaust Gas Flow	Exhaust Gas Flow	Exhaust Gas Flow	Power	Fuel consump.	Fuel consump.	Fuel consump.	Fuel efficiency (exergy)	Fuel consump.	CO	CO_2	O_2	SO_2	HC	CO flux	CO_2 flux	O_2 flux	HC flux	CO flux	CO_2 flux	O_2 flux
	(min)	m/s	m^3/s	L/s	W	L/s	g/s	g/h	g/kWh	g/kWh	%	%	%	ppm	ppm	L/s	L/s	L/s	g/s	g/s	g/s	g/s
Diesel	1	17.4	0.01377611	13.7761096	3704.4	0.00027	0.2232	803.52	78.26	216.91	0.1	1.4	19.5	0	0	0.0138	0.1929	2.6863	0.0000	0.0079	0.1744	1.7664
Diesel	5	20.1	0.01591378	15.9137818	3915.48	0.00027	0.2232	803.52	78.26	205.22	0.1	2.6	19.2	0	2	0.0159	0.4138	3.0554	0.0318	0.0092	0.3741	2.0091
Diesel	10	20.5	0.01623047	16.2304739	4310.04	0.00027	0.2232	803.52	78.26	186.43	0.1	2.9	16.6	0	31	0.0162	0.4707	2.6943	0.5031	0.0093	0.4255	1.7716
Diesel	15	17.1	0.01353859	13.5385905	4310.04	0.00027	0.2232	803.52	78.26	186.43	0.2	2.8	16.3	0	31	0.0271	0.3791	2.2068	0.4197	0.0156	0.3427	1.4510
Diesel	20	23.2	0.01836815	18.3681461	4310.04	0.00027	0.2232	803.52	78.26	186.43	0.2	2.7	16.6	0	31	0.0367	0.4959	3.0491	0.5694	0.0211	0.4484	2.0049
Diesel	1	20.4	0.0161513	16.1513009	3885.84	0.00027	0.2232	803.52	78.26	206.78	0.2	2.2	17.6	0	0	0.0323	0.3553	2.8426	0.0000	0.0186	0.3213	1.8691
Diesel	5	19.8	0.01567626	15.6762626	4020.36	0.00027	0.2232	803.52	78.26	199.86	0.1	2.8	17.5	0	9	0.0157	0.4389	2.7433	0.1411	0.0090	0.3968	1.8038
Diesel	10	20.6	0.01630965	16.309647	4310.04	0.00027	0.2232	803.52	78.26	186.43	0.1	2.8	16.6	0	31	0.0163	0.4567	2.7074	0.5056	0.0094	0.4129	1.7802
Diesel	15	17.6	0.01393446	13.9344557	4310.04	0.00027	0.2232	803.52	78.26	186.43	0.2	2.8	16.4	0	31	0.0279	0.3902	2.2853	0.4320	0.0160	0.3528	1.5026
Diesel	20	19.5	0.01543874	15.4387435	4310.04	0.00027	0.2232	803.52	78.26	186.43	0.2	2.7	16.6	0	31	0.0309	0.4168	2.5628	0.4786	0.0178	0.3769	1.6851
Refined Palm Oil	1	12.2	0.00965911	9.65911132	2660.5	0.00025	0.2323	836.28	95.24	314.33	0.16	2.6	17.1	0	27	0.0155	0.2511	1.6517	0.2608	0.0089	0.2271	1.0861
Refined Palm Oil	5	22	0.01741807	17.4180696	2660.5	0.00025	0.2323	836.28	95.24	314.33	0.23	2.8	16.6	0	47	0.0401	0.4877	2.8914	0.8186	0.0230	0.4409	1.9012
Refined Palm Oil	10	17.5	0.01385528	13.8552826	2896.7	0.00025	0.2323	836.28	95.24	288.70	0.23	2.9	16.4	0	49	0.0319	0.4018	2.2723	0.6789	0.0183	0.3633	1.4941
Refined Palm Oil	15	16.5	0.01306355	13.0635522	2896.7	0.00025	0.2323	836.28	95.24	288.70	0.22	2.9	16	0	49	0.0287	0.3788	2.0902	0.6401	0.0165	0.3425	1.3744
Refined Palm Oil	20	17	0.01345942	13.4594174	2896.7	0.00025	0.2323	836.28	95.24	288.70	0.22	2.9	15.5	0	34	0.0296	0.3903	2.0862	0.4576	0.0170	0.3529	1.3717
Refined Palm Oil	1	20.4	0.0161513	16.1513009	2896.7	0.00027	0.2453	883.2	95.24	304.90	0.19	2.7	16.9	0	31	0.0307	0.4361	2.7296	0.5007	0.0177	0.3943	1.7948
Refined Palm Oil	5	20.6	0.01630965	16.309647	2896.7	0.00027	0.2453	883.2	95.24	304.90	0.22	2.9	16.6	0	46	0.0359	0.4730	2.7074	0.7502	0.0206	0.4276	1.7802
Refined Palm Oil	10	19.5	0.01543874	15.4387435	2896.7	0.00027	0.2453	883.2	95.24	304.90	0.22	2.9	16.3	0	49	0.0340	0.4477	2.5165	0.7565	0.0195	0.4048	1.6547

Fuel	Sample	Exhaust Gas Flow	Exhaust Gas Flow	Exhaust Gas Flow	Power	Fuel consump.	Fuel consump.	Fuel consump.	Fuel efficiency (exergy)	Fuel consump.	CO	CO_2	O_2	SO_2	HC	CO flux	CO_2 flux	O_2 flux	HC flux	CO flux	CO_2 flux	O_2 flux
	(min)	m/s	m^3/s	L/s	W	L/s	g/s	g/h	g/kWh	g/kWh	%	%	%	ppm	ppm	L/s	L/s	L/s	g/s	g/s	g/s	g/s
Refined Palm Oil	15	19.1	0.01512205	15.1220513	2896.7	0.00027	0.2453	883.2	95.24	304.90	0.23	2.9	15.4	0	51	0.0348	0.4385	2.3288	0.7712	0.0200	0.3965	1.5313
Refined Palm Oil	20	21.1	0.01670551	16.7055122	2896.7	0.00027	0.2453	883.2	95.24	304.90	0.2	2.7	16	0	49	0.0334	0.4510	2.6729	0.8186	0.0192	0.4078	1.7575
Waste Cooking Oil	1	16.6	0.01314273	13.1427252	2598.2	0.00018	0.1678	603.9	97.10	232.43	0.14	3.4	15.9	0	14	0.0184	0.4469	2.0897	0.1840	0.0106	0.4040	1.3740
Waste Cooking Oil	5	16.4	0.01298438	12.9843792	2831.0	0.00018	0.1678	603.9	97.10	213.32	0.14	3.6	15.6	0	23	0.0182	0.4674	2.0256	0.2986	0.0105	0.4226	1.3319
Waste Cooking Oil	10	17.6	0.01393446	13.9344557	3096.4	0.00018	0.1678	603.9	97.10	195.03	0.15	3.5	15.7	0	24	0.0209	0.4877	2.1877	0.3344	0.0120	0.4409	1.4385
Waste Cooking Oil	15	16.6	0.01314273	13.1427252	3274.2	0.00018	0.1678	603.9	97.10	184.44	0.15	3.4	15.8	0	24	0.0197	0.4469	2.0766	0.3154	0.0113	0.4040	1.3654
Waste Cooking Oil	20	21.5	0.0170222	17.0222044	3502.3	0.00018	0.1678	603.9	97.10	172.43	0.15	3.4	15.8	0	25	0.0255	0.5788	2.6895	0.4256	0.0147	0.5233	1.7684
Waste Cooking Oil	1	17.4	0.01377611	13.7761096	2831.0	0.00018	0.1678	603.9	97.10	213.32	0.14	3.5	15.7	0	19	0.0193	0.4822	2.1628	0.2617	0.0111	0.4359	1.4221
Waste Cooking Oil	5	17.8	0.0140928	14.0928018	2831.0	0.00018	0.1678	603.9	97.10	213.32	0.14	3.5	15.7	0	23	0.0197	0.4932	2.2126	0.3241	0.0114	0.4459	1.4548
Waste Cooking Oil	10	16.6	0.01314273	13.1427252	3096.4	0.00018	0.1678	603.9	97.10	195.03	0.15	3.4	15.7	0	25	0.0197	0.4469	2.0634	0.3286	0.0113	0.4040	1.3568
Waste Cooking Oil	15	16.4	0.01298438	12.9843792	3274.2	0.00018	0.1678	603.9	97.10	184.44	0.15	3.4	15.7	0	25	0.0195	0.4415	2.0385	0.3246	0.0112	0.3991	1.3404
Waste Cooking Oil	20	17.8	0.0140928	14.0928018	3274.2	0.00018	0.1678	603.9	97.10	184.44	0.15	3.4	15.7	0	25	0.0211	0.4792	2.2126	0.3523	0.0122	0.4332	1.4548

9.5. Annex 5. Journal per reviewed manuscript published as academic merit to present the doctoral thesis

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Article

Bioenergy on Islands: An Environmental Comparison of Continental Palm Oil vs. Local Waste Cooking Oil for Electricity Generation

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Abstract: Energy security on islands is a challenging issue due to their isolation from energy markets and fossil fuel dependence. In addition, islands' average energy intensity has increased in recent years due to economic development. This research explores the environmental performance of two alternative non-variable bioelectricity feedstocks to increase energy resilience on islands. The study was developed for the Galápagos islands to address the environmental impacts from the direct use of waste cooking oil (WCO) and refined palm oil (RPO) to produce 1 MWh using the life cycle assessment methodological framework. A combination of primary and secondary data sources was used. The results show better performance for the electricity derived from WCO in all the impact categories considered when compared to RPO.

Keywords: biofuels; bioelectricity; islands; life cycle assessment; bioenergy; biomass; sustainable islands

1. Introduction

The energy share of most islands is highly dependent on imported fossil fuels, which exposes them to volatile oil prices, limits economic development, and degrades local natural resources. On average, 88% of the total electricity demand in small island developing states (SIDS) is met by fossil fuels, while the remaining 12% is supplied primarily by hydropower, followed by wind energy and biomass in lower proportions [1]. As an illustrative example, in the island countries of the Caribbean Community (CARICOM), 89.7% of the total installed electricity capacity corresponds to fossil fuel technologies and just 10.2% comes from renewables [2]. Besides this, between the years 2000 and 2015, the average energy intensity (total energy consumption/GDP) in islands has increased by 23.4% with a corresponding emission intensity (total emissions/GDP) increase by 12.4% [3]. This ongoing energy dependence fails to establish a precedent for global action to mitigate the long-term consequences of climate change, which pose a particularly acute threat to islands.

From 2010, the number of peer-reviewed publications about renewable energy in islands has nearly tripled, mainly because of the special attention that some intergovernmental organizations (like the Intergovernmental Panel on Climate Change) have given to island nations as they recognize islands' vulnerability to climate change [4].

Most studies have focused on variable rather than base renewable energy resources such as biomass. Surrop (2018) identified 41 studies published focused on wind, solar, and ocean-based technologies and just 12 studies about bioenergy in small island developing states (SIDS) during the 2010–2017 period [4].

Studies regarding the potential use of alternative biomass feedstocks for energy production in islands are on topics as diverse as biodiesel production on Crete [5], coconut oil electricity generation in the Pacific Islands [6], biogas production from animal waste in Indonesia [7], forest-waste-derived fuel with waste cooking oil in Taiwan [8], biogas from animal manure in the Canary Islands [9], biomass-fueled combined heat and power (CHP) in Åland Islands [10], and perennial tree pruning biomass for electricity generation in Greece [11]. Biomass research in Ecuador has addressed the energy potential of some residues from important agricultural commodities [12–15]. In addition, liquid and gaseous biofuel potential generation has also being studied by some authors [16–19].

There are some existing efforts in many SIDS to use biomass to contribute to the decarbonization of their energy matrixes and to reduce their dependence on imported fuels. The use of vegetable oil for electricity generation has been explored mainly by the Pacific Islands. Vanuatu has two 4 MW diesel engines on Efate (the capital) running on a mixture of 30% coconut oil and 70% petroleum, and 15% of the electricity generated comes from coconut oil [20]. The island of Tokelau declared in 2011 its intention to become the world's first 100% renewable country. This is to be achieved by a photovoltaic minigrid on each of the three islands which together would provide 90% of the electricity demand with the remaining 10% to come from coconut oil. Samoa also presents small-scale coconut oil utilization by its power utility [21].

The feasibility of using waste cooking oil (WCO) as an alternative energy feedstock in islands has also been addressed in some research evaluating the potential of biodiesel (via recycled cooking oil) use in Singapore [22] and feasibility of Langkawi waste cooking oil (WCO)-derived biodiesel [23].

Life cycle assessment (LCA) is a quantitative methodological framework to assess the environmental performance of products and services throughout their life cycle. LCA has been used with success to assess the environmental sustainability of bioenergy systems [24–27]. Existing environmental impact studies of biofuels derived from oleaginous feedstocks have mainly focused on biodiesel, such as life cycle analysis of biodiesel production [28], comparative life cycle assessment of diesel production from crude palm oil and waste cooking oil via pyrolysis [29], comparative life cycle assessment of alternative strategies for energy recovery from used cooking oil [30], substitutable biodiesel feedstocks for the U.K. [31], and the used-cooking-oil-to-biodiesel chain in Europe [32].

Furthermore, some authors have studied the combustion emissions of transesterified WCO, mainly in automotive sources, such as the effects of fuel injection pressure on the performance and emissions of a diesel engine fueled with waste cooking oil biodiesel–diesel blends [33], butyl-biodiesel production from waste cooking oil, and fuel properties and emission performance [34], among others.

As shown, although some research has been conducted on the environmental impacts and emissions performance of oleaginous derived fuels, few authors have addressed these issues from the perspective of its straight use as a fuel (non-transesterified) in fixed sources for electricity production [35,36].

In addition, converting waste streams such as waste edible oil into valuable resources represents a three-win solution, dealing simultaneously with human security, pollution, and energy recovery [37]. Circular Economy (CE) is an emerging alternative concept to a traditional linear economy (make, use, dispose) in which resources are kept in use for as long as possible, extracting the maximum value from them whilst in use, and recovering and regenerating products and materials at the end of each service life [38]. The use of waste flows as an energy source is complementary to CE principles [39].

As in the case of most islands, electricity generation in the Galápagos Islands is heavily based on fossil fuels. According to its energy balance, 89% of the electricity produced in the islands comes from fossil fuels, 8.2% from wind, 2.5% from solar, and 0.1% from biofuels [40]. According to Noboa et al. [41], to progressively replace fossil-based energy in Ecuador, other types of non-conventional renewable technologies such as biomass (solid, liquid, and gas) must be developed.

Galápagos has endured severe environmental and economic impacts from fossil fuel spills on its marine reserve. The most serious was caused by a spill from a tanker in 2001, at San Cristóbal Island. A total of 662,447 L of diesel and fuel oil was spilt into the sea. This disaster triggered the decision to foster renewable energy implementation in the islands. In this context, "The Zero Fossil Fuels" initiative was adopted [42]. One component of this project is a biofuel program that aims to reduce the environmental footprint attributed to fossil fuel usage through partial replacement with vegetable oils. In addition, the risks associated with fossil fuel transportation from the mainland to the islands could also be addressed. The biodegradation rate of oleaginous biofuels is 80.4%–91.2% after 30 days, while fossil diesel only reaches 24.5% biodegradation during the same period [43]. Floreana Island is the smallest (172.29 km^2) of the inhabited islands of the Galápagos archipelago. It is located 1000 km from Continental Ecuador [44]. Since 2010, the biofuel pilot program has operated on the island using pure *Jatropha curcas* oil as an energy source in three dual electricity generators which can work indiscriminately with 100% diesel, 100% pure vegetable oil, or any proportion of blends among those. The thermoelectrical group produces 256,713 kWh per year [40]. The current electricity generation by source in Galápagos is shown in Table 1.

Table 1. Electricity generation by source in Galápagos.

	Energy by Source (kWh)					Fuel Used Per Island (L)	
Island	**Diesel**	**Wind**	**Solar**	**Jatropha**	**Total**	**Diesel**	**Jatropha Oil**
San Cristobal	9,924,334	3,864,393	17,250		13,805,977	2,929,824	
Santa Cruz	27,732,054	38,267	1,194,922		28,965,243	7,532,996	
Isabela	4,411,835				4,411,835	1,340,016	
Floreana	208,015		3112	48,698	259,825	74,944	18,367
Total	**42,276,238**	**3,902,660**	**1,215,284**	**48,698**	**47,442,879**	**11,877,780**	**18,367**

Source: (Ministry of Electricity and Renewable Energy of Ecuador (MEER), 2015).

The biofuel program also seeks to reach other islands in the future. The estimated biofuel demand for a B20 blend (20% biofuel/80% diesel) for the San Cristobal and Isabela islands is 585,964.4 and 268,003.2 L of biofuel per year, respectively [45].

In terms of electricity generation, Floreana´s biofuel pilot project has tracked the efficiency of diesel and jatropha oil in terms of kWh produced per liter of fuel: 3.43 and 2.64, respectively [40]. Although pure jatropha oil is the current sole biofuel source for electricity generation in Floreana, just 18.7% of the total electricity is produced on the island because of the absence of a robust supply chain. *Jatropha curcas* production is exclusively based on the collection of mature fruits from plants used as living fences in Manabí province, located in the coastal region of continental Ecuador; agricultural production of the plant at commercial scale is nonexistent in the country. For this reason, it is important to identify environmentally friendly alternatives to permit the permanence of the biofuel project in the islands. As seen in Table 1, the proportions of jatropha oil and diesel are 19.6% vs. 80.4%, respectively [40].

In this context, the goal of this study is to evaluate from an environmental perspective two biomass alternatives for the generation of electricity on islands: refined palm oil (RPO) and waste cooking oil (WCO). The study was developed for the Galápagos Islands due to the singularity of its ecosystem and because of its proactive policy framework aimed to explore the integration of different renewable energy sources.

2. Materials and Methods

Life cycle assessment (LCA) was performed following the standardized method ISO 14040 [46]. The data used were primarily obtained from processes studied in situ, but to some extent, generic LCA data were used, e.g., for the use of fuels in energy supply and transport, while emissions and electricity generation yield from the direct use of RPO and WCO were measured in a test system.

2.1. Goal and Scope

The goal of the present study is to evaluate impacts through a complete life cycle assessment of electricity produced from two potential biofuel sources, (a) refined palm oil (RPO) produced on continental land and (b) locally produced clean waste cooking oil (WCO) in line with CE precepts, and to evaluate whether the production and use of new biofuels can help to reduce fossil fuel imports to islands.

2.2. Functional Unit

The final functional unit (FU) of this study was defined as 1 MWh produced on Floreana Island.

2.3. Life Cycle Inventory

The inventory analysis was developed according to ISO 14040 standards [46] and includes the required energy and material (input) flows as well as products, co-products, emissions, and wastes (outputs) emitted to the environment during all the considered processes.

2.4. System Boundary and Data Sources

2.4.1. Palm-Oil-Based Electricity Product System

In situ inventory data were collected for the five production stages included in this part of the study: (i) palm oil plantation, (ii) palm oil production, (iii) crude palm oil extraction, (iv) palm oil refining (Manabí province), and (v) electricity generation (Floreana Island). Transportation at all stages was included. Figure 1 describes the boundaries of this production system.

2.4.2. Waste Vegetable Oil (WCO) Electricity Product System

In this section of the study, a hypothetical WCO production system on Santa Cruz Island was studied; its boundaries include (i) washing containers, (ii) WCO collection and transportation to the plant, (iii) delivery of WCO from the collection point to the plant, (iv) pre-treatment, (v) processing at the cleaning facility, and (v) transportation to the electricity plant. Unit output: in this phase, 1 metric ton of recovered WCO was used as the unit output.

It must be mentioned that the WCO is assumed to be a waste product. Therefore, the agricultural and industrial production phases are not included, according to standard procedure for the life cycle of waste [47,48]. Figure 2 describes the boundaries of this production system.

2.5. Emissions Testing in Electricity Generation

Primary data were required to compile the emissions inventory of electricity generation as these data were not available. Therefore, an emissions test was carried out in similar conditions to those on Floreana Island using RPO and WCO. A model TESTO 350 emission gas analyzer was used to determine the following parameters: carbon dioxide (CO_2), carbon monoxide (CO), and hydrocarbons (HC) [49].

One metric ton of RPO was purchased from a local provider, and to acquire the same amount of WCO, 30% was collected from five different locations and 70% was purchased from a local cooking oil recycler. The WCO was decanted and filtered in a press filter. It must be mentioned that this recycling company exports 100,000 L of WCO monthly to the European Union where it is converted to biodiesel [50].

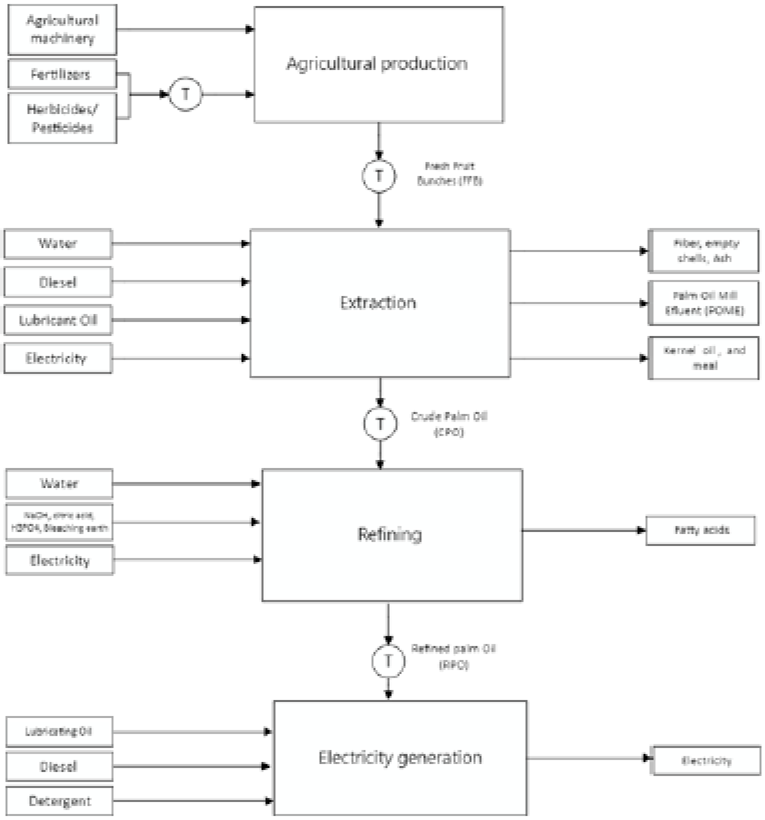

Figure 1. Refined palm oil (RPO) based electricity system boundaries.

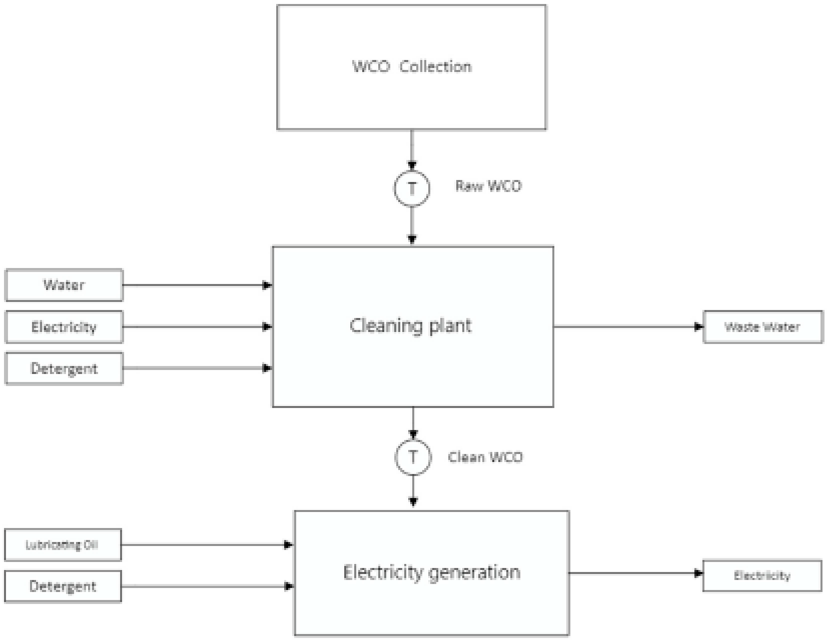

Figure 2. Waste cooking oil (WCO) based electricity system boundaries.

The emission testing was carried out in Quito city in a test system provided by the Institute of Geological and Energy Research of Ecuador (IIGE, by its acronym in Spanish). The test system consists of a direct diesel injection, horizontal, single-cylinder, four-stroke engine of brand YANMAR, - NFD 13, adapted to an electricity generator. An emission sampler was installed by the end of the exhaust pipe where the TESTO 350 emission sampling probe was set. A combustion emission measurement trial was performed for each of the fuel batches. Figure 3 shows the reception, filtration and test emissions performed.

Figure 3. (**A**) WCO received in containers, (**B**) WCO filtration, (**C**) Emission testing.

2.6. Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) method used in this study was the CML 2001 (baseline), a problem-oriented method developed by the Institute of Environmental Sciences of the University of Leiden [51]. This methodology uses the damage-oriented approach or endpoint approach for impact assessment. The impact categories considered in this methodology include the following: carcinogens, respiratory organics and inorganics, climate change, ionizing radiation, ozone layer depletion, ecotoxicity, acidification/eutrophication, land use, and mineral and fossil fuel use.

Simapro version 9.0.033 software was used to calculate the impacts determined by the abovementioned method. A contribution analysis was performed to understand the contributions of specific processes and pollutants to the total impact scores per impact category, and to find the reasons for the differences in environmental impacts between RPO and WCO.

3. Emissions Testing Results

The results are shown in Table 2. These figures are consistent with data registered by Souza (2012) [52]. To estimate the use of the cogeneration unit, the average electricity production for 15 years of life expectancy was assumed from the Ecoinvent database.

Table 2. Emissions from the generation of 1 MWh using diesel, Waste Cooking Oil (WCO), and Refined Palm Oil (RPO).

Fuel Type	CO	CO_2	Hydrocarbons
	kg/MWh	kg/MWh	kg/MWh
Diesel	10.977	322.076	28.8
RPO	23.63	483.85	86.30
WCO	13.48	499.14	37.40

CO emissions were in lower concentration in assays performed with diesel fuel. This fact can be related to the physical properties of the fuel that show their effect during its use in an internal combustion engine [53]. In general terms, diesel fuel has been reported to contain a larger amount of energy per mass or volume unit than vegetable oils [54]. In addition, WCO registered a lower CO emission factor than RPO. In such a context, this issue can be associated with the chemical modification that cooking oil may suffer during its use. These changes can affect its properties, such as viscosity or calorific value, which are also relevant for determining its performance in an internal combustion engine [54].

The CO emission figures registered during the experimental test are concordant with the CO_2 figures as well. This issue is highlighted by the fact that the diesel appears the most efficient choice in terms of energy and that WCO showed better performance when compared to RCO. In this context, it is affirmed that WCO is a better alternative as a fuel despite being considered a waste material.

Regarding the HC content, a trend like that for CO was found. Despite diesel fuel having no oxygen content in its composition, other properties such as its viscosity (determining fuel injection and air–fuel blending inside the engine) [55] and calorific value caused the combustion efficiency to reach results better than those of the assayed oxygenated fuels. In addition, WCO appeared to be a better fuel when compared to RPO. This can be associated with the partial hydrogenation that oils suffer during the cooking process due to their contact with water at high temperatures [56]. Saturation implies augmented hydrogen content in the oil composition; hence, its calorific value and viscosity increase at a similar rate [57]. The electricity generation test results show fuel consumption levels of 0.216 L/kWh for WCO, 0.328 L/kWh for RPO, and 0.162 L /kWh for diesel.

4. Life Cycle Inventory Results

4.1. *Palm-Oil-Based Electricity Production Inventory*

Electricity generation from palm oil on islands has mainly being focused on its byproducts [58–60]. In this study we aimed to explore the environmental impacts related to the direct use of RPO as an electricity feedstock on islands.

The Latin American region exports 1.9 million t of palm oil per year [61]. In Ecuador, the crop contributes 4% of the agricultural gross domestic product (GDP). The production of this commodity presented annual growth of 8% from 2010 to 2016, becoming the seventh -largest agricultural export and one of the most dynamic industries in the country. In the last five years, 42% of palm oil produced in Ecuador was consumed internally, while 58% was exported for a total of USD 271,000,000. Palm oil production in Ecuador accounts for 300,000 hectares with total investment of 2.2 billion USD and generates 127,000 jobs [62].

According to the National Federation of Palm Oil producers (FEDEPALMA), 78,737 t, equivalent to 70,154,667 L, was exported in 2018 [63]. This number shows that the potential biofuel demand for the Galápagos islands could be easily satisfied by palm oil alone.

In situ data collection was performed for each of the stages described in Section 2.4.1.

4.1.1. Agricultural Phase

The input data of materials and energy required to produce 1 t of palm oil fresh fruit bunches (FFB) (the unit output in this phase) were addressed. The cultivation stage includes all agricultural activities dedicated to the production of immature/mature plants. The selection of the agricultural area for this case study was supported by the Palm Oil Improvement Unit of the National Institute of Agricultural Research of Ecuador (INIAP, by its acronym in Spanish). The area is located at latitude: 0°11′22.79″ S, longitude: 79°12′8.62″ W and represents the typical palm oil agricultural systems of Esmeraldas province, one of the largest producers in Ecuador. The data collected were the result of field visits and experts' criteria. The yield was defined as an average obtained from field research and statistics developed by INIAP [64]. Regarding land-use change, although palm oil cultivation is linked to deforestation mainly in the Amazonian region of Ecuador [65], the selected productive zone does not present this pattern because it has been under production for 60 years, while the studied crops have an average age of 12 years. Therefore, no land-use changes were attributed in this study.

It must be mentioned that the selected plantations have a better production yield when compared to the national average due to the application of best agricultural practices recommended by the research center [64]. Information regarding fertilizers, pesticides, herbicides, machinery use, and input transportation was collected during visits.

The average agricultural conditions of the productive units studied are shown in Table 3.

Table 3. Plantation characteristics.

Characteristic	No.
FFB yield (t ha year)	18
Plant density (ha)	142
Plantation lifetime (years)	25
Total area (ha)	2800

Source: In situ surveys.

Average yearly yields, as well as inventory data of fertilizers, herbicides, pesticides, and energy usage during plantation and harvesting, were collected in situ. Adjustments were made using recommendation charts developed by INIAP [64].

Fertilizers: The total amount of applied fertilizers in the studied plantations was calculated for 25 years as the productive period of the crop. Manure-based fertilization in palm oil crops is not a common practice in Ecuador; hence, it was not included in the study.

Herbicides, pesticides: Data on herbicides and pesticide used per FFB t produced in Ecuador were compiled during site visits; adjustments were made by INIAP.

Energy: In terms of energy consumption, one source was identified: gasoline used on agricultural machinery (a motorized bush cutter).

Transport: The transportation of agricultural inputs from the warehouse to the plantation in EURO 1, 10 t capacity trucks was included using ton-kilometer (tkm) units.

Emissions at the Agricultural Phase

The emission outputs analyzed in this part of the study were emissions to air, water, and soil which occurred during the agricultural production of 1 FFB ton.

Emissions derived from the use of fertilizers were determined using methodologies and models developed by the authors of [66–70]. The Pest LCI2.0.8 model was used for determining pesticide emissions to soil, air, and water [71]. Heavy metal emissions were calculated using the models and methodologies developed by the authors of [72,73] and [74]. Emissions from fertilizer production and pesticides used in the plantation were determined using the Ecoinvent database [75].

Inputs were assigned for 1 t of FFB (Table 4). Finally, the values were processed in Simpapro 9.0.0.3 software considering their origination and end: nature or technosphere.

4.1.2. Industrial Phase Inventory

Extraction Process

The palm oil mill type studied is in Esmeraldas province at latitude: 0°1′34.25″ N, longitude: 79°23′54.65″ W. The facility has a processing capacity of 5.6 t of FFB per hour (90 t of FFB per day). The distance from the plantation to the facility is 31.5 km by road. Process data were obtained from monthly reports provided by the management department. The average crude palm oil (CPO) yield in the studied oil mill is 0.185 t per ton of FFB processed. Fiber residues, 150 kg per ton processed, are used as fuel for generating steam that supplies 97.6% of the total energy demand of the plant; the rest is purchased from the grid. Nevertheless, a diesel-based electricity generator is used in case of electricity shortage and to start engines. Economic allocation was selected in the extraction phase. Table 5 presents the inputs used in this production phase.

Table 4. Inputs and outputs in the agricultural production of 1 FFB t.

Inputs/Outputs	Unit	Amount
Inputs		
Urea	kg	7.6
Ammonium sulphate	kg	1.4
Triple superphosphate	kg	9.5×10^{-1}
Di ammonium phosphate	kg	2.2×10^{-1}
Potassium sulphate	kg	3.0×10^{-2}
NPK (15–15–15) compound	kg	5.2
Potassium chloride	kg	1.4×10^{1}
Transport	tkm	8.2
CO_2	kg	1.1×10^{3}
Glyphosate	kg	4.1×10^{-1}
Metsulfuron	kg	6.9×10^{-1}
Benfuracarb	kg	6.1×10^{-2}
Gasoline	l	2.0×10^{-1}
Output		
Carbon dioxide (air)	kg	1.0×10
Ammonia (air)	kg	7.6×10
Nitrate (air)	kg	1.3
Dinitrogen monoxide (air)	kg	8.5×10^{-2}
Nitrogen monoxide (air)	kg	8.5×10^{-3}
Glyphosate (air)	kg	1.4×10^{-2}
Metsulfuron-methyl (air)	kg	2.3×10^{-3}
Nitrate (groundwater)	kg	1.3
Cadmium (groundwater)	mg	3.8×10^{-1}
Copper (groundwater)	mg	2.3×10
Zinc (groundwater)	mg	4.4×10
Lead (groundwater)	mg	2.0×10^{-1}
Chromium (groundwater)	mg	1.7×10^{2}
Phosphate (river)	kg	8.3×10^{-3}
Glyphosate (river)	kg	3.2×10^{-4}
Metsulfuron-methyl (river)	kg	8.1×10^{6}
Glyphosate (groundwater)	kg	4.4×10^{-2}
Metsulfuron-methyl (groundwater)	kg	5.3×10^{-3}
Glyphosate (soil)	kg	5.9×10^{-1}
Metsulfuron (soil)	kg	5.9×10^{-1}
Cadmium (soil)	mg	6.8
Copper (soil)	mg	4.8×10^{2}
Zinc (soil)	mg	2.5×10^{2}
Lead (soil)	mg	2.5×10
Chromium (soil)	mg	7.5×10^{2}
Nickel (soil)	mg	1.4×10^{2}
FFB	t	1

Emissions at the Industrial Phase

Emissions to water were estimated using the methodology developed by Hosseini et al. [76], and emissions to air using Jungbluth el al. [77].

Emissions to water and air due to the use of the national electricity grid of Ecuador were adapted from Ramirez et al. [78] using the electricity mix for the year 2018. These emissions are included in Tables 5 and 6.

Table 5. Inputs and outputs for the extraction of 1 t of crude palm oil.

Inputs/Outputs	Unit	Amount
Input		
Water	t	5.4
FFB	t	5.1
Lubricating oil	kg	2.7×10^{-3}
Energy, from diesel	kWh	1.4
Transport, truck	tkm	3.1×10
Electricity, continental (EC)	kWh	1.4
Electricity, co-generation biomass	kWh	1.3×10^{2}
Heat and power co-generation unit, building construction	p	4.4×10^{-6}
Heat and power co-generation unit, components	p	1.7×10^{-5}
Heat and power co-generation unit, component construction	p	1.7×10^{-5}
Output		
Carbon dioxide, biogenic (air)	kg	3.2
Methane (air)	kg	1.5×10
Nitrogen oxides (air)	kg	2.0
Particulates, <2.5 um (air)	kg	1.0
Carbon monoxide, biogenic (air)	kg	1.5×10
Methane, biogenic (air)	kg	9.8×10^{-3}
Non-methane volatile organic compounds (NMVOC), (air)	kg	1.3×10^{-2}
Sulfur dioxide (air)	kg	5.6×10^{-2}
Dinitrogen monoxide (air)	kg	5.1×10^{-2}
Acetaldehyde (air)	kg	1.3×10^{-3}
Hydrocarbons, aliphatic, alkanes, unspecified (air)	kg	2.0×10^{-2}
Hydrocarbons, aliphatic, unsaturated (air)	kg	7.0×10^{-2}
Arsenic (air)	kg	2.2×10^{-5}
Benzopyrene, methyl (air)	kg	1.1×10^{-5}
Benzene (air)	kg	2.0×10^{-2}
Bromine (air)	kg	1.3×10^{-3}
Calcium (air)	kg	1.3×10
Cadmium (air)	kg	1.5×10^{-5}
Chlorine (air)	kg	4.0×10^{-3}
Chromium IV (air)	kg	9.0×10^{-7}
Copper (air)	kg	4.9×10^{-4}
Dioxin (air)	kg	7.0×10^{-10}
Ethyl benzoate (air)	kg	6.7×10^{-4}
Fluoride (air)	kg	1.1×10^{-3}
Formaldehyde (air)	kg	2.9×10^{-3}
Benzene, hexachloride (air)	kg	1.6×10^{-10}
Mercury (air)	kg	5.9×10^{-8}
Potassium (air)	kg	5.3×10^{-1}
Magnesium (air)	kg	3.8×10^{-3}
Manganese (air)	kg	3.4×10^{-5}
Sodium (air)	kg	2.9×10^{-2}
Ammonia (air)	kg	3.9×10^{-2}
Nickel (air)	kg	1.3×10^{-4}
Phosphorus (air)	kg	6.7×10^{-3}
Polycyclic aromatic hydrocarbons (air)	kg	2.4×10^{-4}
Lead (air)	kg	5.6×10^{-4}

Table 5. *Cont.*

Inputs/Outputs	Unit	Amount
Phenol, pentachloro- (air)	kg	1.8×10^{-7}
Toluene (air)	kg	6.7×10^{-3}
m-Xylene (air)	kg	2.7×10^{-3}
Zinc (air)	kg	6.7×10^{-3}
Chromium (air)	kg	9.0×10^{-5}
Nitrogen, total (to freshwater)	t	1.0×10^{-2}
Oils, biogenic (to freshwater)	t	6.1×10^{-2}
BOD, biological oxygen demand (to freshwater)	t	3.1×10^{-1}
COD, chemical oxygen demand (to freshwater)	kg	6.7×10^{-1}
Crude palm oil	t	1

Table 6. Inputs and outputs for producing 1 t of RPO.

Inputs/Outputs	Unit	Amount
Input		
Water	L	1.5×10^{2}
CPO	kg	1.0×10^{3}
Bleaching earth	kg	8.0
Phosphoric acid	kg	9.6×10^{-1}
Citric acid	kg	7.7×10^{-1}
Sodium hydroxide	kg	3.4×10^{-1}
Electricity EC grid	kWh	1.6×10
Transport, truck < 10 t, EURO1	tkm	2.1×10^{2}
Output		
RPO	t	1
Fatty acids	kg	7.0×10
Water vapor	m^3	6.3×10
Wastewater from vegetable oil refinery	m^3	8.7×10

4.1.3. Transport

Refining Process

Extracted CPO is transported to a refinery facility located 258 km from the oil mill by road. The refining process removes odors, flavors, and impurities through bleaching and deodorizing methods.

The mass balance of the studied system resulted in a yield of 1 t of RPO per 1.08 t of CPO. The inputs and outputs for this phase are shown in Table 6.

Ground Transportation

The studied palm oil processing mill is located 31.5 km from the plantation in Esmeraldas province, while the refining plant is in Manabí province, 258 km away. Once the oil is extracted, it is transported by a 10 t capacity truck to Timsa port in Guayaquil city. The distance between the processing plant and the port is 326 km by road. Ton-kilometer (tkm) units are included in the study results for each transportation stage.

Assuming the full capacity of a 10 t truck, a total amount of 3260 tkm was estimated. For each metric ton of pure palm oil was assigned 326 tkm for road transportation to Timsa port in Guayaquil city. Finally, once the RPO arrives at Floreana Island, it is transported 0.5 km by truck to the electricity generation facility. The means of transportation selected from the Ecoinvent database in this phase was transport, truck < 10 t, EURO 1.

Marine Transportation

Once the refined palm oil arrives at Timsa port in Guayaquil city, it is shipped to Floreana Island in Galápagos. The route is made by an 834.5 t capacity tanker ship. The route comprises 1283 km to Velasco Ibarra port on Floreana Island. Assuming that the vessel is travelling at full capacity, the allocation results in 1283 tkm for the unit output of 1 Tm of RPO (4119 L). For this component, a 960 t capacity barge ship container with 80% load factor (LF) and empty return was selected from the Ecoinvent database.

4.1.4. Electricity Generation

On Floreana Island, three 89 kW DEUTZ generators of model BF4M101E, year 2010, have been adapted to work with diesel, vegetable oil, or any blend of the two. The fuel currently used is a blend of diesel and pure jatropha oil which varies in proportions according to the availability of the latter. According to the Galápagos energy balance, on average, 9.83 kWh is generated per gallon of vegetable oil [40]. According to the reference information provided by the Galápagos energy balance, it was calculated that 385,086 L of vegetable oil (or 353.085 kg) must be used to generate 1 MWh. Section 3 describes the direct emissions measurement performed. The inputs and outputs of this phase are included in Table 7.

Table 7. Inputs and outputs to produce 1 MWh from RPO.

Inputs/Outputs	Unit	Amount
Input		
RPO	kg	3.5×10^2
Lubricating oil	kg	1.9
Transport, truck < 10 t EURO1	tkm	1.4×10^2
Marine transport 350 t ship	tkm	4.2×10^2
Heat and power co-generation unit, 50 kW electrical, components	p	7.7×10^{-4}
Sodium hypochlorite	kg	1.1×10^{-5}
Water	kg	1.8×10^2
Outputs		
Carbon monoxide, biogenic	kg	2.3×10
Carbon dioxide, biogenic	kg	4.8×10^2
Hydrocarbons	kg	8.6×10
Electricity	MWh	1

4.2. *WCO In Situ Production Inventory*

Waste cooking oil (WCO) is defined as an oil-based substance that has been used in cooking or food preparation and is no longer suitable for human consumption [79]. The disposal of large amounts of WCO has become a problematic issue in most countries. WCO cannot be discharged into drains or sewers because this will lead to blockages, odor, or vermin problems and may also pollute watercourses, causing problems to wildlife [80]. It is also a prohibited substance and will cause problems if dumped in municipal solid waste landfills or municipal sewage treatment plants [81]. When WCO reaches natural ecosystems, such as rivers, aquifers, or subsoil, the environmental consequences can be severe. In terms of economic and energy costs, the inappropriate disposal of used cooking oil represents 3 kWh and about 1€, respectively, per kg of WCO delivered to the sewer system [82]. These risks must be highlighted in a fragile ecosystem such as Galápagos Islands.

Using WCO as an alternative fuel for energy generation could therefore be a sustainable solution not only for disposal but also for greenhouse gas (GHG) emission abatement.

Many countries around the world, e.g., Portugal, Greece, Italy, Spain, Belgium, Denmark, China, U.S.A, Australia, Germany, the U.K., and Korea, have implemented regulations for using WCO for energy [83]. Also, WCO could potentially be used as an in-situ-produced biofuel, reducing environmental and capital costs in line with circular economy principles.

The use of this potential energy source would also reduce in a significant manner the environmental impact of fossil-fuel-based energy generation in islands. In this context, collecting and recycling WCO contributes to simultaneously solving three environmental problems: waste reduction by reuse/recovery, reduction of fossil fuel dependence, and reduction of pollutant emissions [84]. Furthermore, studies developed by Caldeira (2018) showed advantages regarding the water footprint for WCO when compared with other biodiesel feedstocks, finding the lowest impact for WCO with 0.03 world m^2eq/kg, while for palm oil, the results were 1.26 world m^2eq/kg [85].

According to Capuano (2017) [35], the use of WCO in diesel engines is much more feasible for the stationary production of electrical and thermal energy; an illustrative example is the Vegawatt system developed by Owl Power Company in the U.S.A. which produces electricity in situ using WCO [86], and in low-speed diesel engines, i.e., those of large ships [87], rather than for automotive applications. In this last case, direct use of WCO on a large scale is currently not feasible due to the need for changes in the design of the engines, as well as for organization of the distribution network. A comparison of the physical and chemical properties of palm oil, WCO, and diesel is shown in Table 8.

Table 8. Comparison of the physical and chemical properties of refined palm oil (RPO), Waste Cooking Oil (WCO), and diesel.

Properties	RPO	WCO	Diesel
Viscosity (eSt) (40 °C)	39–43	31–50	2.5–4.5
Density (15 °C) (kg/m^3)	860–920	910–943	820–860
Heating value (MJ/kg)	36.5–40.1	32.2–41.8	43.0–46.0
Cetane number	42–49	36–37	45–56
Flash point (40 °C)	267–304	>250	>52.0
Iodine value	35–66	98–128	–
Sources	[88–92]	[93–95]	[81,96–98]

The diesel consumption for electricity generation in CARICOM's islands is 218 million liters per year or 8.4 M GJ [99]. Taking into account the annual vegetable oil consumption of the Caribbean region [100], the recovery ratio determined by Pardo (2013) [101], and the urban population in each island, we estimate a hypothetical availability of 124 million liters per year of regenerated WCO or 4.2 GJ which could be used to replace 44% of diesel imports for electricity production.

The current population of the Galápagos Islands is 25,500 people [102]. In addition, according to the annual Visitor Report for the protected areas of Galápagos [103], an average of 228,306 tourists (floating population) visit the archipelago every year with average permanency of 7 days; 77% of the total, 159,814 tourists, stay on Santa Cruz Island.

On the other hand, the average annual amount of edible cooking oil used per capita in the Latin American region is 20 kg [104]. The food´s oil absorption ratio is 25% [105]. Nevertheless, the real WCO recovery ratio in the region is estimated to be from 20% to 45% [101,106]. Thus, we can determine an average WCO potential recovery of between 114,259.70 and 257,084.33 kg, or between 121,287.99 and 272,898 L, per year on Santa Cruz Island. According to the Galápagos energy balance, Floreana Island uses 74,944 L of diesel and 18,367 L of vegetable oil (*Jatropha curcas*) per year as fuels in its dual electricity generators [40]. This fuel demand can be easily covered by WCO produced on Santa Cruz Island.

In addition, the implementation of a WCO value chain could develop a new local industry, creating local employment and reducing foreign exchange expenditures on energy.

In situ and bibliographical data were collected for each of the following production stages: (i) washing containers, (ii) WCO collection and transportation to plant, (iii) delivery of WCO from the collection point to the plant, (iv) pre-treatment, (v) processing at the cleaning facility, and (v) transportation to the electricity plant.

4.2.1. WCO Collection

A hypothetical WCO collection system was drawn in Santa Cruz Island, the most-populated island and main touristic destination of the Galápagos. One hundred and twenty potential WCO collection sites were identified through in situ visits: 32 restaurants and 88 hotels.

Two collection routes were drawn (Figure 4). The first, in the southeast zone of the island, is 4.47 km, and the second, in the northeast zone of the island, is 3.72 km, totaling 8.7 km. Both collecting routes end in a hypothetical cleaning facility located in the electricity company facilities at the following coordinates: latitude 0°44′37.81″ S, longitude 90°19′11.97″ W.

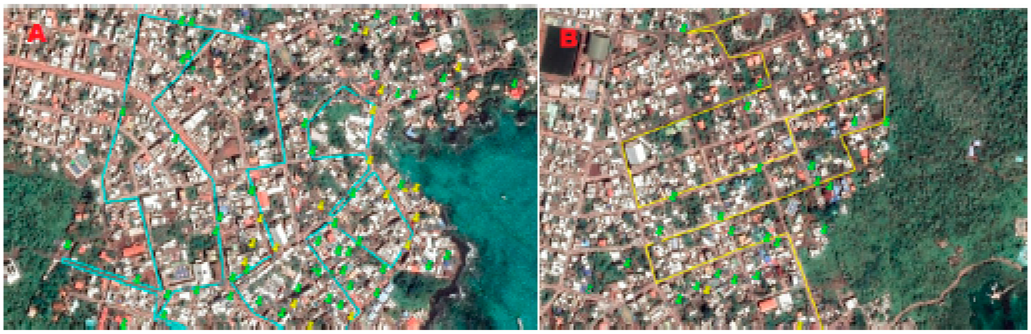

Figure 4. Collection circuits drafted for Santa Cruz Island: (**A**) South circuit, (**B**) North Circuit.

4.2.2. WCO Cleaning

The WCO processing phase comprises the following activities: (i) washing containers, (ii) oil regeneration, (iii) pre-heating, (iv) decantation, (v) sieving and pumping, and (vi) extraction/filtration. The use of electricity and water was estimated according to Lombardi (2018) [30].

The required materials and infrastructure were estimated according to Ripa (2014) [37]. Table 9 shows the inputs required to produce one metric ton of regenerated waste cooking oil.

Table 9. Inputs and outputs to produce 1 MWh from WCO.

Inputs/Outputs	Unit	Amount
Input		
Water	L	9.8
Transport, truck < 10 t	tkm	8.0
Electricity grid Galápagos	kWh	4.6×10
Steel, low-alloyed steel production	p	6.4×10^{-2}
Pump, 40 W production	p	2.2×10^{-2}
Sodium hypochlorite	kg	1.1×10^{-5}
Output		
Wastewater	L	1.2×10^{2}
Clean WCO	t	1

The electricity mix in Santa Cruz Island was modelled in Simapro software according to the technologies reported in the energy balance of the Galápagos Islands [40].

4.2.3. Transport

For the collection phase, we assumed the use of a EURO1 10 t capacity diesel truck; from the Ecoinvent database, 8.7 tkm was assigned.

The treated WCO is transported by sea from the Santa Cruz port 56.49 km to Simon Bolivar port on Floreana Island. The transport system to be used in this stage is a cargo catamaran. Assuming that the vessel is travelling at full capacity, it was assigned 56.49 tkm for the unit output of 1 Tm of pure palm oil (1088 L). For this component of the process, a barge ship, container, 960 t, 80% LF, empty return, global market, Economic was selected from the Ecoinvent database.

4.2.4. Electricity Generation

The electricity production process is described in Section 4.1.4. The inputs and outputs in this phase are detailed in Table 10, including the direct emissions measurement performed.

Table 10. Inputs and outputs to produce 1 MWh from WCO.

Inputs/Outputs	Unit	Amount
Input		
Lubricating oil	kg	1.9×10
Transport, truck < 10 t, EURO1	tkm	3
Marine transport 350 t ship	tkm	1.9×10
Heat and power co-generation unit, 50 kW electrical, components	p	7.7×10^{-4}
Sodium hypochlorite	kg	1.1×10^{-5}
Water	kg	1.8×10^{2}
WCO	kg	3.5×10^{2}
Output		
Carbon monoxide, biogenic	kg	1.3×10
Carbon dioxide, biogenic	kg	4.9×10^{2}
Hydrocarbons	kg	8.6×10
Electricity	MWh	1

5. Life Cycle Impact Assessment Results

5.1. Comparison of Results

The main comparative results from method CML 2001 for RPO and WCO LCA per impact category are shown in Table 11. The results per contributor per type of material are illustrated in Figures 5 and 6.

Table 11. Main impact categorization results per 1 MWh derived from WCO and RPO.

Impact Category	Abbreviation	Unit	MWh RPO	MWh WCO
Marine sediment ecotox.	MSE	kg 1,4–DB eq	1.6×10^{2}	2.7×10
Photochemical oxidation	POP	kg C_2H_4 eq	7.6×10^{-1}	3.7×10^{-1}
Land competition	LC	m^2a	1.0×10^{2}	2.3×10^{-1}
Terrestrial ecotoxicity	TET	kg 1,4–DB eq	2.1×10^{-1}	3.3×10^{-3}
Marine aquatic ecotox.	MET	kg 1,4–DB eq	1.4×10^{2}	2.5×10
Human toxicity	HTP	kg 1,4–DB eq	1.7×10^{2}	7.7
Ozone layer depletion	ODP	kg CFC–11eq	1.6×10^{-5}	1.7×10^{-6}
Global warming	GWP	kg CO_2 eq	4.5×10^{2}	2.4×10
Eutrophication	EP	kg PO_4–eq	7.9	1.6×10^{-2}
Acidification	AP	kg SO_2 eq	3.6	1.1×10^{-1}
Abiotic depletion	ADP	kg Sb eq	1.7	2.3×10^{-1}

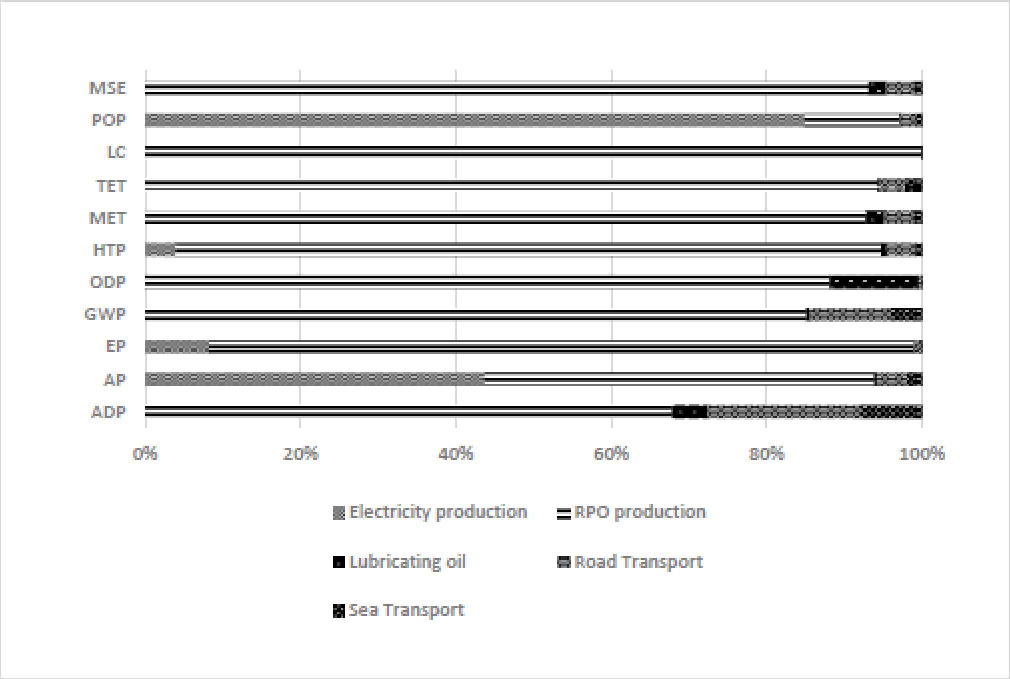

Figure 5. Contribution analysis per process for RPO-based electricity generation. Abbreviations are presented in Table 11.

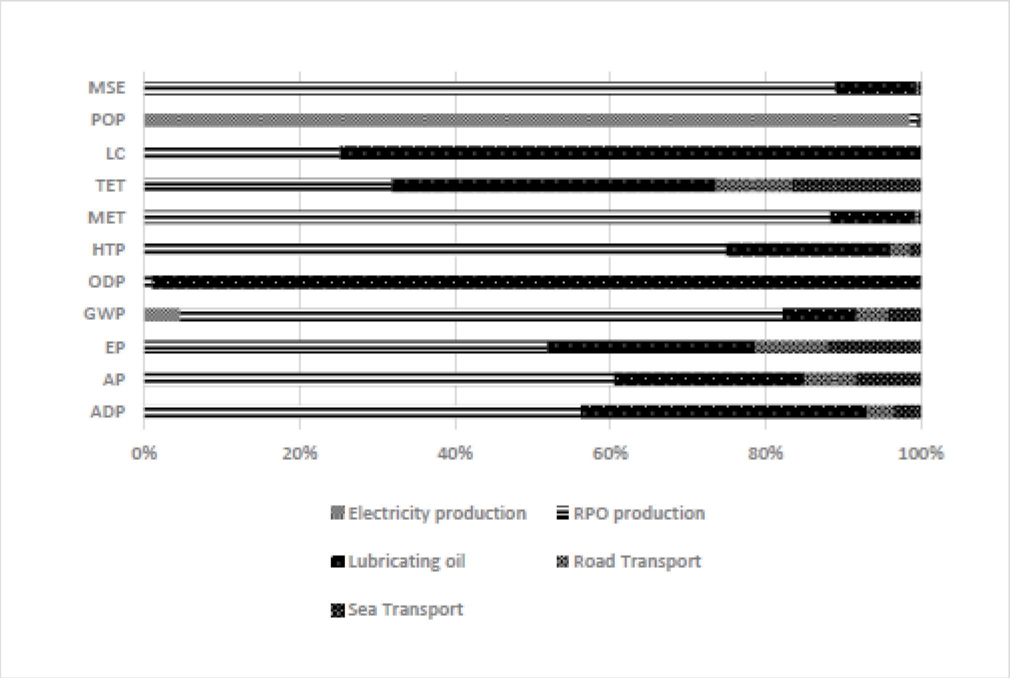

Figure 6. Contribution analysis per process for WCO-based electricity generation. Abbreviations are presented in Table 11.

5.2. Interpretation

Regarding global warming (GWP), the life cycle of WCO decreases this indicator by 94.6% compared with RPO. The primary source of greenhouse gases in the RPO production cycle is methane production from wastewater and landfill emissions in the oil extraction phase. In terms of abiotic depletion, WCO performs 97% better than RPO because of the reduced use of processing facilities and the avoidance of fertilizers (mainly urea) in its production. RPO performed worse than WCO in terms of acidification, mainly because of ammonia release derived from the use of urea as a fertilizer and the use of pesticides in the agricultural production phase. Regarding eutrophication potential, RPO presents a 90% greater contribution than WCO because of the chemical oxygen demand (COD) and nitrogen present in the wastewater at the extraction phase. On the other hand, WCO performs 7.56 times better than RPO regarding ozone depletion over five years. In terms of human toxicity at 20 years, WCO performs 95% better than RPO. The results show 27% better performance of WCO when compared with RPO regarding photochemical oxidation. In terms of terrestrial and marine ecotoxicity, mainly because of the use of herbicides, RPO performs 98% and 71% worse than WCO, respectively. The results comparison for each impact category is illustrated in Figure 7.

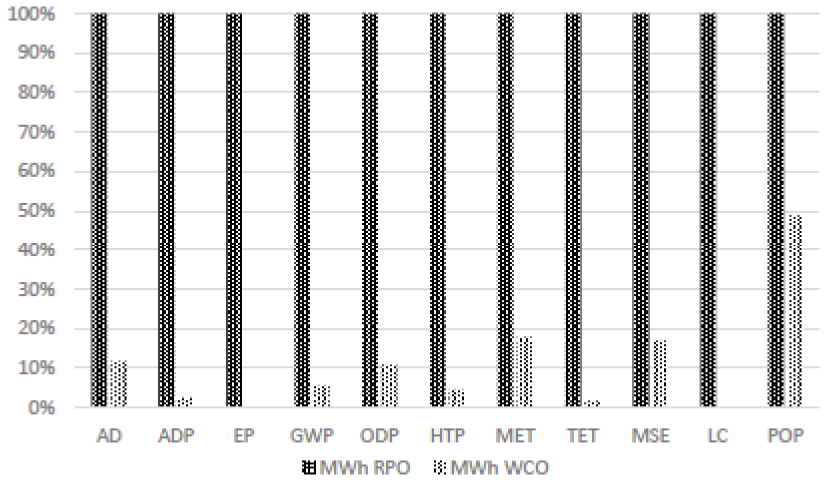

Figure 7. Comparison of the characterization results of WCO- vs. RPO-based electricity generation in Galápagos. Abbreviations are presented in Table 11.

6. Discussion

As mentioned in the introduction, there is increasing interest in the research of non-variable energy sources on islands to reduce their dependency on imported fossil fuels. Some studies have been conducted regarding the use of alternative oleaginous sources for energy generation on islands; nevertheless, most of them have focused on biofuels produced through transesterification processes. Few studies have analyzed the use of alternative energy sources such as WCO in island systems. Moreover, there is a lack of research regarding the environmental impacts of electricity generation from biomass feedstocks in this type of ecosystem.

In this context, our study aimed to evaluate the environmental impact of the direct use of non-transesterified feedstock options for electricity generation on islands—imported RPO vs. locally produced WCO—in addition to providing direct data on the emissions from the combustion of these two materials.

According to the results, straight RPO-based electricity production accounts for a higher environmental footprint when compared to WCO in all impact categories, as presented in Figure 7.

The impact category results presented in Table 11 are coherent in magnitude with similar studies developed for *Jatropha curcas*-based electricity generation [27].

As mentioned, the main strength of this study is the presentation of a full-chain LCA for both feedstocks to provide inputs to decision-makers when analyzing bioenergy options for islands, and the provision of firsthand measurement data from combustion emissions.

In terms of limitations, we must mention that although the selected agricultural production area represents the average production conditions of palm oil in Ecuador, a bigger sample including other producer provinces and other land-use changes could increase the representativeness of the FFB production system in the country.

Regarding emissions testing and electricity generation yield, our results are in good agreement with the literature [36,97,107]; nevertheless, we observed some contradicting conclusions reported in other studies [108,109]. It is possible to get contradicting results in emissions studies because they are dependent on many variables, such as different physical conditions, experimental atmospheres, test equipment, and, especially, the combustion chamber. In this regard, one of the main weaknesses of this study is that the emissions test was performed in a 10 kW–200 rpm engine; this could result in lower efficiency and higher emissions. In addition, it is very difficult to predict the chemical composition of WCO as it is dependent on many factors like temperature, exposure to air, and cooked food composition, among others [110]. These variables can impact the performance of the final material when combusted. Another important limitation of the study is the limited number of emission measurements performed in conditions other than those of Floreana Island's electricity generation group.

Regarding the LCA data and results, as mentioned, most of the existing studies analyzed transesterified fuels, which made result comparisons difficult as our study relied on straight use. Nevertheless, the calculated environmental burden reduction from WCO usage is still consistent with the literature [37,48]. According to our results, RPO is the main contributor to GWP with 305 kg CO_2 eq, from which around 40% is CH_4 derived from wastewater produced during the production of crude palm oil. Palm Oil Mill Effluent (POME) is an underutilized liquid waste stream from palm oil mills which is generated during the palm oil extraction/decanting process and is often seen as a serious environmental issue. Nevertheless, POME could be used as a good biomethane source, which can also be used for energy production. Promising research has addressed the potential of POME to generate biohydrogen and biomethane (or a mixture of these: biohythane) for energy purposes [111]. These alternative POME utilizations could dramatically reduce the GHG footprint during the production phase. The second-largest GHG emission source identified in this study is transport (marine and road), accounting for 61 kg CO_2 eq; it is important to mention that this footprint could be reduced if agricultural production areas are located closer to refining facilities and to marine ports.

In addition, N_2O contributes 42 kg CO_2 eq; this GHG is commonly derived from the use of nitrogen-based fertilization and was estimated as a function of applied N, as mentioned. It is important to mention that by-products of palm oil production can also be used for fertilization: the use of 300 kg of empty FFB could be equivalent to 4.8 kg of potassium chloride (KCL), 0.25 kg diammonium hydrogen phosphate (DAP), and 10 g of borate per plant [112].

In the case of WCO, the higher contributor to GWP (91% of the total) is the use of electricity from the Galápagos electricity grid which, as mentioned, is heavily reliant on fossil fuels. This footprint could be reduced if more renewable energy is integrated into the system. The second GHG source is road and marine transportation.

Regarding RPO-based electricity acidification potential, the main contributor with 1.6 kg SO_2 eq is ammonia emissions derived from N fertilizer application during the agricultural production of FFB. Thus, it is important to stress the environmental benefits related to the reduction of chemical nitrogenated fertilization. The second contributor, with 20%, is NOx emission derived from the use of fossil fuels in transport and energy generation during the production process. Regarding WCO-based electricity, the main source of acidification in this study came from SO_2 and NOx from the combustion of fossil fuels during electricity generation in the Galápagos grid; these impacts are relevant in sensible ecosystems such as islands. According to Glynn (2018) [113], if CO_2 emissions are not reduced, ocean warming and acidification are projected to drastically reduce or eliminate coral reefs from the Galápagos between the years of 2026 and 2035.

In RPO electricity production, chemical oxygen demand (COD) contributes 62% of the total eutrophication potential (PO_4 eq); this process is linked to the high amount of oxidizable pollutants found in the wastewater from the extraction phase. In terms of abiotic depletion (ADP), 56% of the total antimony (Sb) equivalent is attributed to the use of fossil fuels in RPO production, including fuels used for input production and materials.

Considering the rich and sensible marine ecosystem of the Galápagos, the main contributor to marine ecotoxicity is wastewater from WCO cleaning with 80.6 1,4 Dichlorobenzene equivalent (1,4–DB eq). In this regard, adequate final disposal of the wastewater in this process is crucial to reducing this environmental impact.

Some of the unanswered questions and future research derived from this study are to (i) study the willingness of business owners to provide WCO in Galápagos or other islands; (ii) conduct emissions testing in conditions similar to those of the electric group located on Floreana Island; (iii) analyze the environmental impacts of WCO disposed in the sewage system in Galápagos; (iv) determine the impact of the potential energy usage of other by-products not exploited in the production cycle, such as palm kernel residues and sludges from the extraction phase; and (v) analyze the land-use change impact of productive zones with high carbon content, such as the Amazonian region.

7. Conclusions

The results of this study indicate that a system based on locally generated waste such as WCO is a superior alternative to continental RPO in environmental terms. This is mostly associated with the fact that WCO is a waste material which does not have environmental or resource impacts associated with its production and processing. The life cycle of RPO includes agricultural production, industrial processing, and transport. In addition, fewer resources are used in the in situ processing and transport of WCO compared to RPO.

Both feedstocks, RPO and WCO, independent of their production impacts, meet the conditions for being used as an energy source for non-variable electricity generation on islands. The experience of Galápagos with the direct use of vegetable oils provides valid evidence for the use of non-transesterified oleaginous feedstocks for electricity generation which can be extrapolated to other islands.

Nevertheless, further analysis should be performed to understand the flows and the current and future availability of WCO on any island that considers this as an option. It is also important to study in more detail the impacts of incorrect WCO disposal in fragile ecosystems such as islands.

Regarding RPO, it is important to include impacts related to land-use change in agricultural productive zones where deforestation is an issue.

Finally, the electricity production test shows that WCO has higher electricity yield when compared to RPO. This can be associated with the partial hydrogenation that oils suffer during the cooking process due to their contact with water at high temperatures.

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