

**UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ**

**Colegio de Ciencias e Ingenierías**

**Technical feasibility for large scale production of biochar as catalyst  
for waste motor oil catalytic cracking**

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**Ingeniería Química**

Trabajo de fin de carrera presentado como requisito  
para la obtención del título de Ingeniería Química

Quito, 20 de diciembre de 2022

# **UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ**

**Colegio de Ciencias e Ingenierías**

## **HOJA DE CALIFICACIÓN DE TRABAJO DE FIN DE CARRERA**

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motor oil catalytic cracking**

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Quito, 20 de diciembre de 2022

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## RESUMEN

Sectores agrícolas e industrias buscan alternativas para sus desechos y generar productos de valor agregado. La remediación de suelos y materiales ricos en carbono son unas de las alternativas exploradas. Sin embargo, para demostrar la contribución real del bio carbón para la mitigación de contaminación, se necesitan estudios de huella de carbono y evaluaciones de ciclo de vida (LCA). El presente estudio determina el potencial de la producción a gran escala de bio carbón, usando como materia prima la cascarilla de arroz y su aplicación como catalizador para el craqueo de aceite de motor desechado. Con el propósito de evaluar su viabilidad, se realizaron experimentos usando pirólisis para generar bio carbón y craqueo de aceite de motor usado. De esta forma, datos cinéticos comparando las reacciones de craqueo térmico y catalítico, determinaron el uso favorable de bio carbón. La caracterización del BC con imagen SEM y espectros FTIR, evidenció su estructura porosa y el alto contenido de carbono. Se determinaron dos posibles escenarios para el estudio de viabilidad. Primero, usar cascarilla de plantas ubicadas en Durán (Guayas), mientras que el segundo considera el aceite de Quito (Pichincha), analizando únicamente el transporte y pirólisis. Finalmente se demostró que en ambos casos el tratamiento térmico de cascarilla de arroz es favorable para mitigar las emisiones de CO<sub>2</sub> a la atmósfera. Aunque en el segundo caso, el transporte genera emisiones considerables y altos requerimientos energéticos, por lo cual no es viable optar por este escenario.

**Palabras clave:** bio carbón, pirólisis, craqueo, gases de efecto invernadero (GEI), huella de carbono, ruta abierta.

## ABSTRACT

Agricultural sectors and industries seek alternatives for their waste and generate value-added products. Soil remediation and carbon-rich materials are some of the explored alternatives. Although, to demonstrate the real contribution of biochar for pollution mitigation in production, carbon footprint studies and life cycle assessments (LCA) are needed. The present study determines the potential of large-scale production of biochar, using rice husk as raw material and its use as a catalyst for the waste motor oil cracking. To evaluate its feasibility, experiments were carried out using pyrolysis to generate biochar and cracking of waste motor oil (WMO). In this way, kinetic data comparing the thermal and catalytic cracking reactions determined the favorable use of biochar. Characterization with SEM image and FTIR spectra evidenced its porous structure and high carbon content. Two possible scenarios for the study were determined. First, using rice husk from plants located in Durán (Guayas), while the second considers oil from Quito (Pichincha), analyzing only transport and pyrolysis process. Finally, it was evidenced that in both cases the heat treatment of rice husks is favorable to mitigate CO<sub>2</sub> emissions into the atmosphere. Although in the second case, transport generates considerable GHG emissions and high energy requirements, for which it is not feasible to choose this transport route or scenario.

**Key words:** biochar, pyrolysis, cracking, greenhouse gas (GHG), carbon footprint, open route.

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## I. Introduction

Alternatives have been sought to decrease greenhouse gas emissions globally and take climate change, as a real challenge. Among other problems, massive amounts of agricultural residues are produced globally, without proper ending. Livestock farming feeding materials, carbon providers, and in-situ incineration or gasification are examples of main crop residues uses [1]. Rice is the second most produced food in the world followed by wheat. Its growing conditions depends on temperatures between 20 °C and 35 °C, clay, or sandy texture soils with a pH 6.6 [2]. To obtain rice as a final product, it must go through three main processes: harvesting, drying, and milling. During milling, the rice grain is husked and separated from the sterile palea and glume, both main components of rice husk. From these residues, rice husk makes up 20% of the processed rice. Particularly, Ecuador reported 2 million tons of rice residues by 2014, including rice husk and straw [2].

There are several biological and thermo-chemical transformation processes for revalorizing biomass residues into valuable products [3]. Among them, biomass pyrolysis has attracted attention for producing biochar, a carbonaceous material with high surface area and porosity, thermal stability, high adsorption capacity, and carbon stability [3], [4]. Biomass pyrolysis can be affected by conditions like biomass type, pyrolysis temperatures, residence time and heating rate [5], [6]. This method includes the use of an inert environment during the process of biomass thermal decomposition at high temperatures [7]. In the last decade, biochar has played a key role in environmental practices like soil amendment, adsorption of organic dyes and heavy metals or carbon capture and storage (CCS). But it is also gaining interest in the catalytic market, due to its highly porous structures and high carbon content [3].

Engine oil or other lubricant products from petroleum refining process are a mixture of mineral, synthetic or processed oils with additives. The extensive range of these products are mainly used for the operation of internal combustion engines, as they serve as surface wear protection and can reduce friction [8]. Nevertheless, due to the increase of the global automotive fleet, the demand for these goods has also increased. Approximately lubricating derivatives constitute 53% of the total oil consumption, and half of this percentage is consumed in automotive industries [9]. Therefore, the unregulated storage of used lubricants and waste has affected multiple environmental aspects such as soil recovery capacity or water bodies and sources [10]. As an alternative to reduce environmental impacts of Waste Motor Oil (WMO), a variety of options for recovering oil have been reported in literature, like generation of biofuels, especially biodiesel or diesel-like products [1]. In this way, it has also been shown that the use of catalyst generated from crop residues helps improve the performance and purity of these biofuels [11], [12] producing a considerable amount of waste without correct treatment.

Since 2019, in Ecuador was evidenced a growth of 13% of the automotive fleet, most of this percentage is reflected in Quito and Guayaquil, which also leads to an increase in the consumption of lubricants and their waste. It is also known that on average a 4-cylinder engine needs from 3.5 to 4.5 L of motor oil, 6-cylinder engine need an average of 5 L and an 8-cylinder engine require from 5.5 to 7.5L [13].

This investigation focuses on the evaluation of the technical feasibility and carbon footprint for large-scale production of rice husk biochar as catalyst for waste motor oil catalytic cracking. Specific activities have been performed, such as chemical engineering test to obtain kinetic data from WMO catalytic and thermal cracking, technical feasibility analysis for large scale biochar generation and calculation of carbon footprint indicator for

this process, including greenhouse gas (GHG) emissions from pyrolysis and biomass transportation.

## **II. Materials and Methods**

### **a. Biochar Synthesis**

Rice husk was obtained from local markets. The obtained biomass needed separation from other residues found in the packaging that could debouch in pyrolysis equipment damage. Then, 10 g are initially weighed, which must go through a drying process in a heat-resistant glass dish for 24 h to evaporate most of the water content in the sample that could cause a higher bio-oil production, as it is considered a by-product of this process. Dried RH is placed on a graphite heat-resistant plate to perform pyrolysis reaction using nitrogen as inert gas for 1h at 700° C [14]. The obtained biochar is stored in a desiccator.

### **b. Waste Motor Oil Recovery Process**

Used engine oil was recovered from a single car, not mixed with other solvents or oily products. Pre-treatments must undergo before the cracking reaction. Sieve was performed to avoid the influence of external residues found in WMO that could affect the distillation process and debouch in equipment damages. Oil was heated and stirred at 100° C and 350 rpm for 2 h to evaporate most water content. Then oil was sifted again.

### **c. Cracking Reaction**

For the cracking reaction, 40 mL of pre-treated oil was placed in a 250 mL distillation flask, and 0.04 wt% of biochar is added. Likewise, 40-50 °C water is added in a Precision Scientific Petroleum Herzog equipment. It is pre-heated for 15

min at 50 W [15]. Then, the distillation flask is placed in the heater section under a fume cupboard where the vapor obtained through cracking will be condensed in a graduated cylinder. The equipment resistance is then set to 80 W. Oil temperature and recovered oil are measured every 5 min for a reaction time of 3 h. Resulting gases are also stored in a Tedlar sampling bag as a product.

#### d. Kinetic Study

The kinetic constant for the cracking reaction was obtained using the next equation, where  $M_A$  is the variable mass of WMO changing during reaction and  $M_{A0}$  is the initial mass of WMO:

$$-\ln\left(\frac{M_A}{M_{A0}}\right) \quad (1)$$

$M_A$  was calculated using the following expression:

$$M_A = M_{A0} - m_{condensate} - m_{gas} \quad (2)$$

In this case,  $m_{condensate}$  is the mass of the condensate oil collected throughout cracking process in the cylinder and  $m_{gas}$  is the gas accumulating in the Tedlar bag. The relation between the total mass of the condensate product and gas was used to obtain  $m_{gas}$ . Therefore, slope of equation (1) vs time graphic shows the kinetic constant of the reaction.

#### e. Biochar Characterization

Imaging was used to characterize biochar by Scanning Electron Microscope (SEM) and analysis by Agilent Tech. Fourier-Transform infrared spectroscopy Carry 630 (FTIR).

#### **f. WMO and RH availability**

For WMO availability, an approximation was made based on data from the automotive fleet growth registered in 2018 from Pichincha and Guayas, as both provinces recorded the largest automotive fleet in Ecuador. For this reason, it was considered WMO came from vehicles like SUV, wagon, and automobile. On average, motor oil changes 3 times per year and consume an estimated 5L, these approximations were assumed to calculate the total available volume for both provinces.

In case of RH, availability was evaluated based on the crop residues from rice industries registered in Guayas [2]. Based on this data, an estimation of the RH feedstock was made based on the biochar yield calculated through the pyrolysis experiment using the following equation:

$$RH \text{ biochar yield } [\%] = \frac{\text{Pyrolyzed Biochar } [g]}{\text{Dried Biomass } [g]} \times 100 \quad (3)$$

#### **g. Carbon Footprint Calculations**

The estimation of this indicator is focused on the pyrolysis and transportation of rice husk from a possible large-scale production scenario of using biomass from Durán, Guayas to a hypothetical plant located in Duran (scenario 1) and other in Quito (scenario 2). System boundaries and carbon flow for this study are shown in Figure 1. It was not considered the drying process for this calculation as it consists in

natural drying with no equipment or energy needed and consequently, no CO<sub>2</sub> emissions associated. Both scenarios adopted an open route to estimate the diesel consumption per route, per shipment, energy consumption and GHG emissions for RH mobilization.

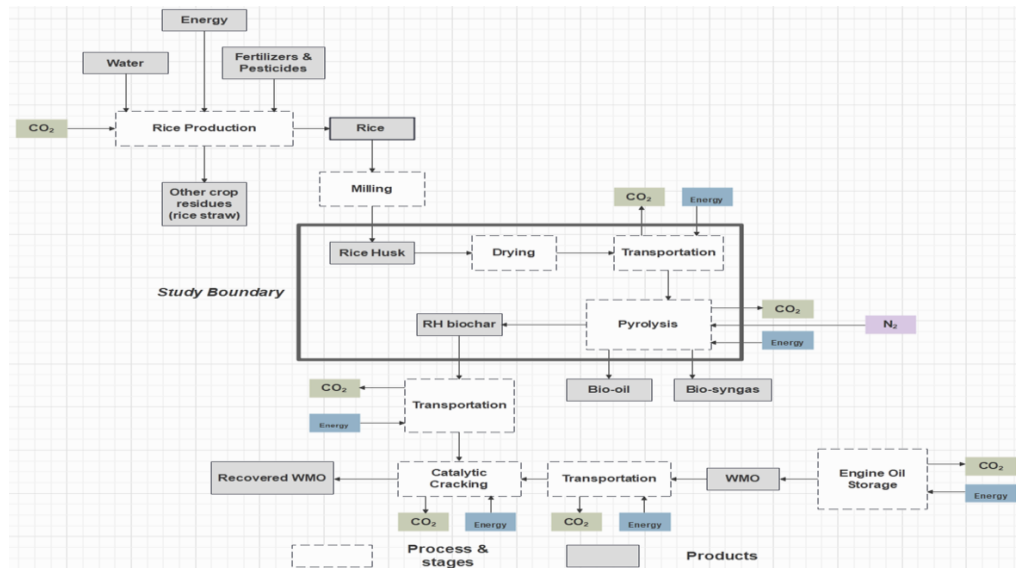


Figure 1. System boundary and carbon flows from rice husk biochar production and application

#### i. Transportation

As a reference, the characteristics of a 6-axle (configuration 4x2) diesel type truck with a charge capacity of 12650 [kg], fuel tank of 320 [L] and a cylinder capacity of 7684 [cc] were used for calculations. Calculation parameters and constants were used for an established flat (Guayas) and hilly (Pichincha) terrains and a 12-24 t MMA truck. The main calculations and equations are based on the EN 16258:2012 normative [16].

Energy consumption factor were obtained using the next equation:



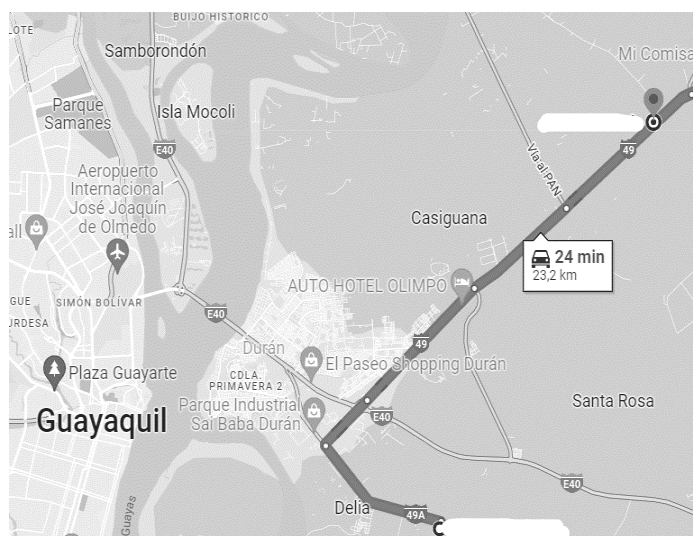
$$E_{Tship}[MJ] = e_T \times F_{ship} \ ; \ E_{Wship}[MJ] = e_W \times F_{ship} \quad (4)$$

Where  $E_{Tship}$  is the energy consumption from “tank to wheel”,  $E_{Wship}$  is the energy consumption from “well to wheel”,  $e_T$  and  $e_W$  are energy consumption factors; and  $F_{ship}$  is the fuel consumption per trip and shipment [16].

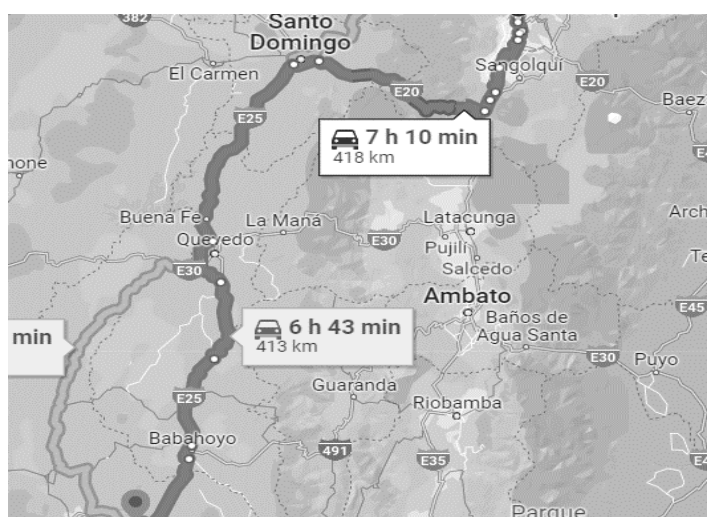
In the same way, GHG emissions factor was obtained using the next equation:

$$G_{Tship}[kgCO_{2e}] = g_T \times F_{ship} \ ; \ G_{Wship}[kgCO_{2e}] = g_W \times F_{ship} \quad 5)$$

Where  $G_{Tship}$  is the GHG emission from “tank to wheel”,  $G_{Wship}$  is the GHG emission from “well to wheel”,  $e_T$  and  $e_W$  are GHG emission factors. For both cases are considered also the additional weight of containers (wood pallets) used for RH, with dimensions of 1000x1200, static load of 2000 kg, dynamic load of 1000 kg and 20 kg each pallet.



(A)



(B)

*Figure 2.* Routes established for transportation energy consumption and GHG emissions for scenario 1 (A) and scenario 2 (B)

ii. Pyrolysis Process

For better understanding, the following data collected from previous studies as laboratory-scale was used to create the large-scale scenario of producing biochar from rice residues:

- Rice Husk Biochar C content 42.82% [5], [17]
- Rice Husk C content 33.5% [18]

Based on previous large-scale Life Cycle Assessment (LCA) studies of biochar production and considering pyrolysis process is an exothermic process, is evidenced that for an estimated flow rate capacity of 10 ton/h, the initial start-up process needs a 58 MJ/ton. In this case, for the possible plant of scenarios 1 and 2 are 1.02 ton/h and 1.09 ton/h respectively, both values are used to estimate energy requirements for start-up process.

In this way, for the approximation of GHG emissions produced with pyrolysis process, the following equation was used:

$$kg\ CO_2eq = (m_{drybiomass} \times y_{RHB} \times \%C_{RiceContent} \times \%C_{RHBContent}) \quad (6)$$

### III. Results and Discussions

#### a. Cracking Results

For thermal cracking, temperature stabilize at 430 °C after a 15 min period, as shown in Figure 1a. Once it is stabilized, the recovered condensate volume increased until obtaining a total of 25.5 mL at 170 min, as is also shown in Figure 1a. On the other hand, for the catalytic cracking, temperature stabilize at 421 °C after a 15 min period, as shown in Figure 1b and the condensate volume increased after stabilization time until obtaining a total of 25.5 mL at 140 min.

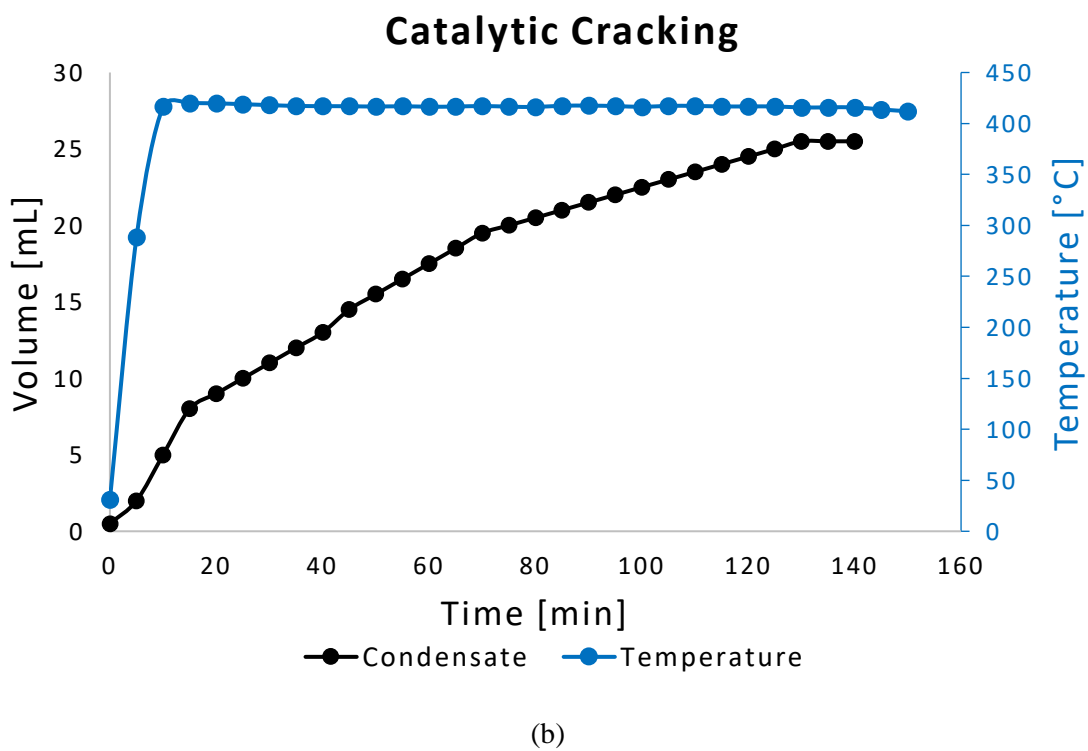
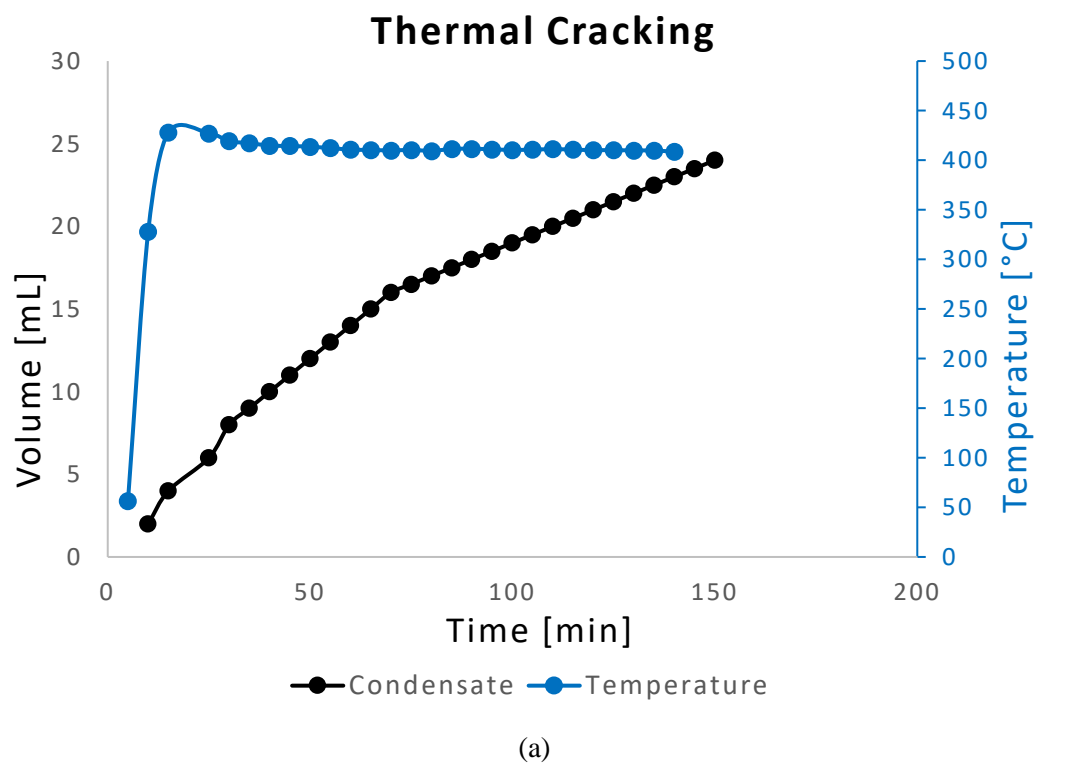


Figure 3. Temperature and condensate volume during thermal (a) and catalytic cracking (b)

Likewise, final mass of WMO was estimated using Equation 2. The WMO and RH biochar added in the distillation flask before catalytic cracking was 40.05 g and 0.16 g respectively. After reaction, the WMO final mass was recorded at 16.52 g, which means a greater conversion rate in comparison of thermal cracking, as it is shown in Figure 2 (right), where thermal reaction reached a 52% of conversion and RH biochar cracking reaction achieved a 56% conversion.

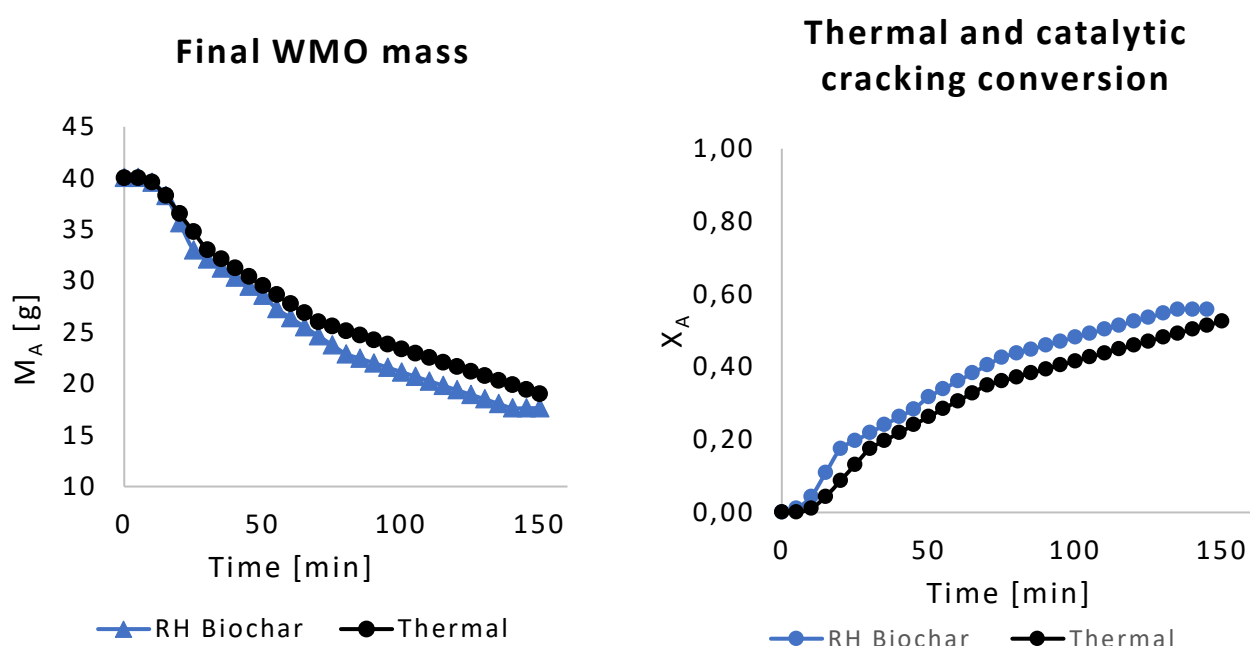


Figure 4. Final WMO mass (left) and conversion (right) over the thermal and catalytic cracking reaction

## b. Kinetic Constants

Kinetic constants were calculated for thermal and RH biochar catalytic cracking using Equation 1 and graphic slopes of this indicator vs time. Table 1 shows

both constants of these first-order reactions, which dependent on the WMO concentration through time. As it was evidenced in Figure 2, using RH biochar increased the reaction speed, which means using biochar as catalyst meets its goal during the cracking process for recovering WMO. This phenomenon can be related to the porous structure and C content evidenced in the following biochar characterization results.

*Table 1.* Kinetic constants for thermal and catalytic cracking

<b>Reaction</b>	<b>k [L/min]</b>
Thermal	$0.0046 \pm 7.91 \times 10^{-4}$
Catalytic	$0.0069 \pm 6.89 \times 10^{-4}$

### **c. RH biochar characterization**

SEM and FTIR analysis were performed to evidence biochar production. As shown in Figure 3 the porous structure of biochar was seen in the SEM micrograph. Biochar properties like pores volume and size, surface area and functionality depend on pyrolytic temperature and biomass origin [3]. In this case, pyrolysis temperature influence in RH biochar structure and catalyst productivity, same as has been demonstrated during the reaction performance, since 700 °C increase the biochar formation without total decomposition of biomass [14][5]. SEM image exposed the variety of mesopores and macropores shapes obtained from using rice husk feedstock. Pore structure appeared to be following a hilly-like pattern as the macropores increased due to temperature effect [17]. It also relates to the RH composition as it

has been demonstrated that cellulose, lignin, silica, and moisture content affects biochar catalyst patterns in thermal treatments [19].

In the same way, FTIR spectra demonstrated RH biochar contained functional groups such as carbonyl, carboxyl and aromatic compounds as detailed in Table 2. Biochar spectral compartments exhibited the presence of aromatic C=C and C=O stretching bonds, as carboxylic acid displayed at bands of  $2150\text{ cm}^{-1}$ ,  $1970\text{ cm}^{-1}$  and  $1550\text{ cm}^{-1}$  respectively. Unexpectedly silica (silanol) SiOH stretching bond appeared at  $\sim 3757\text{ cm}^{-1}$  [20] and same scenario happened with subcarbonyl bimetallic cluster  $\text{Rh}+(\text{CO})_3$  species show at  $2084\text{ cm}^{-1}$ , which have proven to be quite stable and sensitive to thermal degradation [21]. As pyrolytic temperatures increased, C-O stretching bonds began to disappear, thus directly related to biomass decomposition [22].

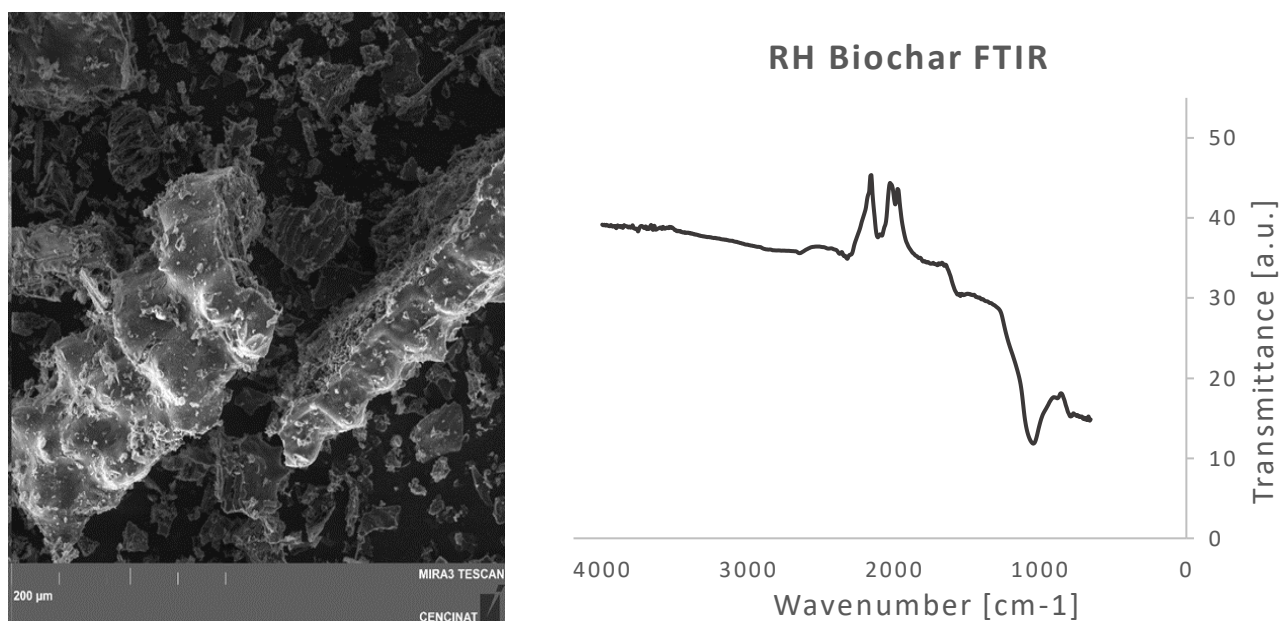


Figure 5. RH biochar SEM image (left) and FTIR (right)

Table 2. Functional groups observed in the FTIR spectra of RH biochar produced at 700 °C

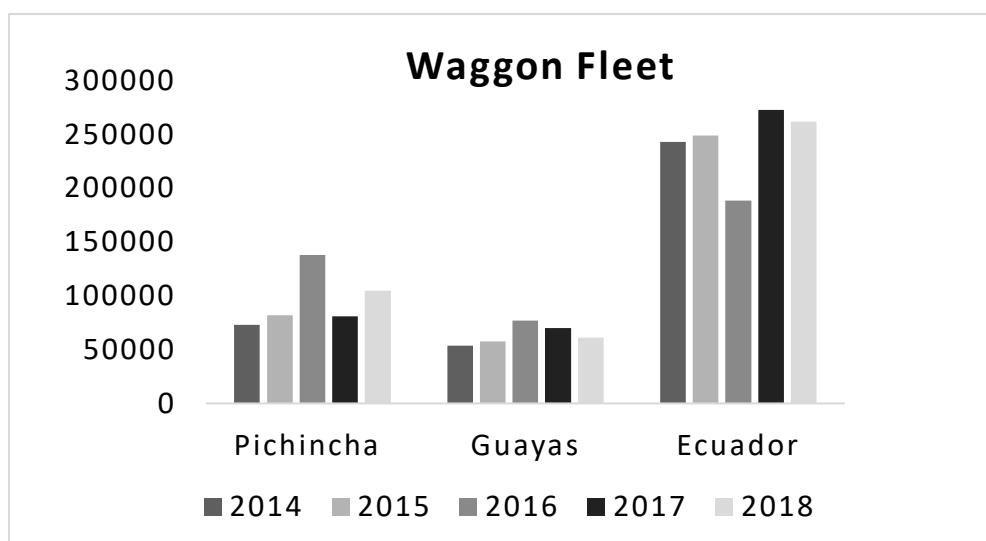
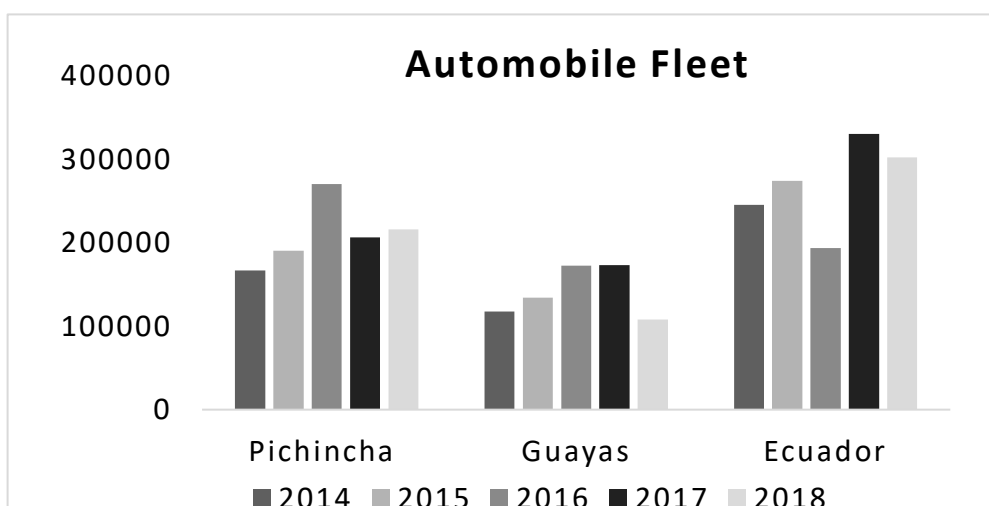
Wave number [cm <sup>-1</sup> ]	Vibration characteristics
3800 – 3500	SiOH stretching
2260 – 2190	C=C stretching
~2084	Rh+(CO) <sub>3</sub>
2000 – 1965	C=O stretching
1610 – 1550	Carboxylic acid
1090 – 1020	Primary amine C-N stretch
~782	Substituent of aromatic rings

#### d. WMO and RH availability study

In Ecuador, since 2014 automotive fleet growing trend has been demonstrated in cities such as Quito and Guayaquil, same that have the highest population density. By 2021, the sale of vehicles increased by approximately 20%, especially in SUVs, wagons and automobiles [23]. For further understanding, an automobile needs and oil change at least 3 times a year and on average consumes 5L of this lubricant. Environmental pollution related to used lubricating oils increased due to highest usage of this petroleum derivative consumption and lack of regulations, storages, and recycling protocols has been evidenced in the last decade [10]. In this case, the automotive fleet (SUV, wagons, and automobiles) registered in 2018 were used to calculate the availability of engine used oil in Guayas and Pichincha as shown in Figure 6. As a result of this approximation, a total volume of WMO of 8.78 E+06 per year was registered for both provinces. With this indicator was evidenced that there is enough WMO that can be recycled through a catalytic reaction using RH biochar.



Also, being a rice-producing country, an estimation of discarded rice husk per year was performed, showing that the RH produced in Pichincha and Guayas were 165.28 ton and 1.31 E+06 ton respectively. Therefore, with a biochar yield of 43.37% calculated with Equation 3, the study of RH available verified that, in a possible scenario in which WMO large-scale cracking process happens, enough RHB could be produced, as in Guayas and Pichincha the estimated available RH biochar are 7.09 E+01 and 6.27 E+05 for each case.



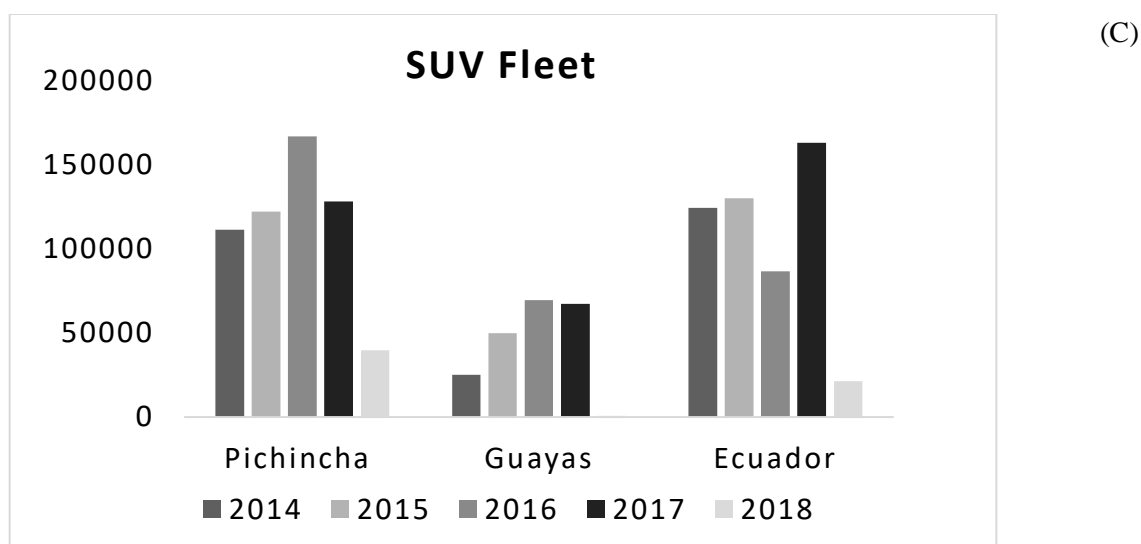


Figure 6. Automobile (A), wagon (B) and SUV (C) fleet registered between 2014 and 2018 in Guayas, Pichincha, and the rest of Ecuador

#### e. Carbon Footprint Results

For scenario 1, transportation energy consumption and GHG emissions per shipment are shown in Table 3. It is necessary to mention that in both cases, each transport services considered one shipment with load in bulk and another empty. Contemplating that for large-scale production of RHB an 18.91 tons of biomass feedstock is needed, to possibly transform WMO registered at previous availability results in Guayas. The open route of transporting from Durán surroundings to Guayas (industrial park zone) with a travel distance of ~24 km, includes a flat road which does not require much force from the truck engine and given trucks charge capacity, one shipment per month is sufficient to meet productions requirements.

RH biochar GHG emissions results for dry feedstock transportation are consistent with the study conducted for the large-scale production of biochar based on

tomato residues, where transportation of 1 ton of crop residues registered 30.8 kg CO<sub>2</sub> eq, while in this case, for 1 ton of RH, only 26.6 kg CO<sub>2</sub> eq are estimated [24].

*Table 3.* Energy Consumption and GHG emissions for shipping service of 18.91 ton of RH in scenario 1

<b>Total Energy Consumption and GHG emissions for shipping service (Guayas)</b>	
Et <sub>total</sub> [MJ]	2893.8136
G <sub>total</sub> [kgCO <sub>2</sub> e]	217.58827

In case of scenario 2, it was decided to carry out a study based on the use of biomass from Durán, as RH produced in Pichincha does not cover the production needs to recover WMO volume generated in Quito. Thus, the open route considered ~420 km distance, including a hilly road which demand highest engine performance and consequently higher energy consumption, as is shown in Table 4. Although this result is higher compared to transportation showed in Table 3, using RH biomass as raw material to produce a value-added product environmental advantage could be obtained compared to the original materials used in catalytic industry [24], [25].

*Table 4.* Energy Consumption and GHG emissions for shipping service of 20.05 ton of RH in scenario 2

<b>Total Energy Consumption and GHG emissions for shipping service (Pichincha)</b>	
Et <sub>total</sub> [MJ]	36546.838
G <sub>total</sub> [kgCO <sub>2</sub> e]	2747.9874

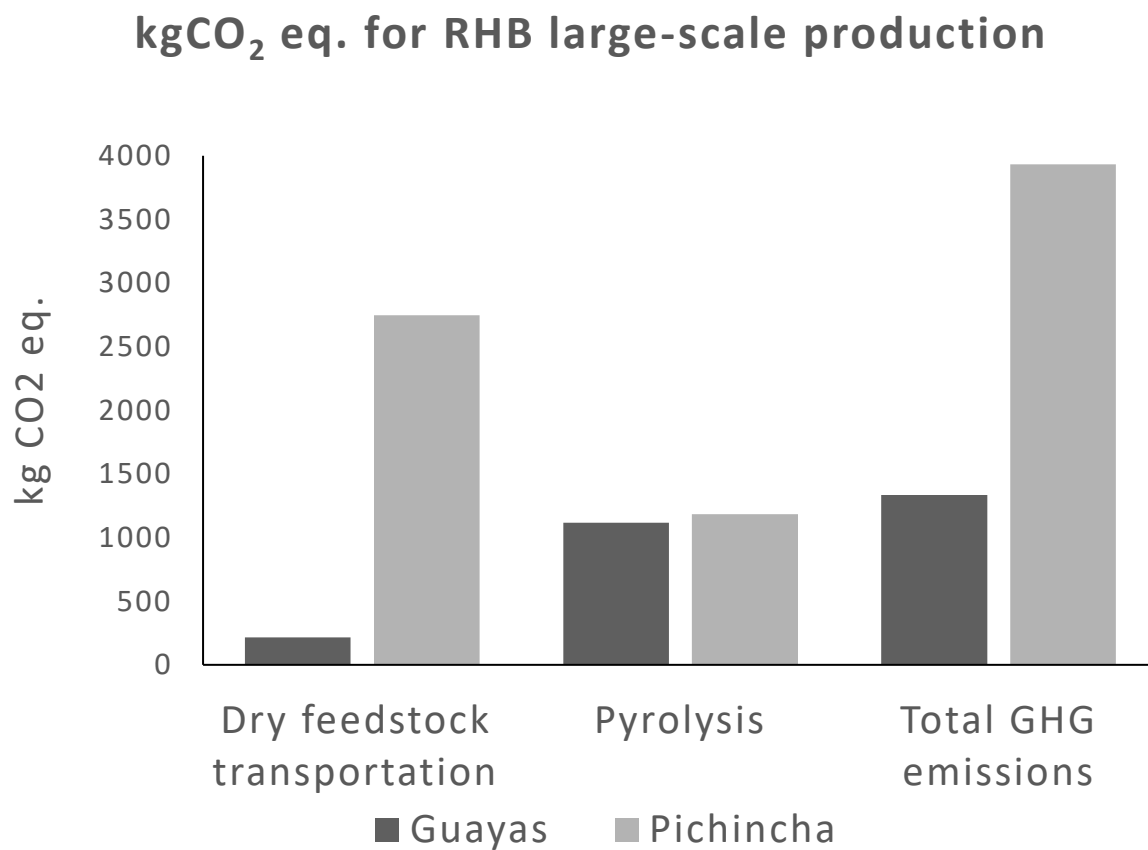
For pyrolysis process in scenarios 1 and 2 results of energy consumption and GHG emissions are shown in table 5 and 6, respectively. Both values were estimated with previous LCA analysis of biomass/crop residues large-scale pyrolysis process. Nevertheless, energy consumption and electricity demand are different in Ecuador, especially in industrial zones in Guayaquil and Quito, which could change the present results. In comparison of recent studies, values are similar for tomato waste pyrolysis, confirming the advantages of using crop residues as raw material [24]. As shown in Figure 7, the most convenient scenario for large-scale production is scenario 1, as it represents the lowest kgCO<sub>2</sub> eq. for a RHB production using ~19 ton of dry feedstock, including transportation and pyrolysis process.

*Table 5.* Energy Consumption and GHG emissions for RH pyrolysis process in scenario 1

<b>RHB Pyrolysis Process Energy Consumption and GHG emissions (Guayas)</b>	
Ettotal [MJ/ton]	5.94682626
RHB Pyrolysis [kgCO <sub>2</sub> e]	1117.29266

*Table 6.* Energy Consumption and GHG emissions for RH pyrolysis process in scenario 1

<b>RHB Pyrolysis Process Energy Consumption and GHG emissions (Pichincha)</b>	
Ettotal [MJ/ton]	6.30578183
RHB Pyrolysis [kgCO <sub>2</sub> e]	1184.73341



*Figure 7.* Carbon emissions from RHB large-scale production with agricultural dry feedstock in scenario 1 (Guayas) and scenario 2 (Pichincha)

#### IV. Conclusions

At the first section of this study, it has been demonstrating the possible use of biochar as a catalyst for improving the thermal cracking of WMO. Showing a new application for biomass residues in catalytic industry. Results obtained showed RH biochar activity and conversion for catalytic cracking are greater compared to thermal reaction. Pyrolysis process obtain a carbon rich material with better pore volume and surface area complementing its great capacity to perform as a catalyst, without losing all biomass content. SEM images and FTIR also complement previous analyses regarding advantages of using crop residues, as raw material for producing carbon-rich materials.

From these results, a feasibility study was carried out for a possible large-scale biochar production. It has been concluded that rice production in an agricultural country, such as Ecuador generates enough biomass to cover a possible demand of recovery process of waste motor oil obtained from the increasing automotive fleet in provinces like Guayas and Pichincha. But its real production viability goes hand in hand with studies of energy consumption and greenhouse gas emissions, which are considered key factors for development a carbon footprint estimation.

In case of scaling the laboratory-scale results obtained, it is recommended to use the scenario 1, since the dry feedstock transportation from Durán to Guayaquil implies a short open route in a flat terrain, which means a lower energy requirement by the truck type with previously detailed characteristics.

On the other hand, delivered dry biomass to Quito, as planned in scenario 2, implies in a highest GHG emissions and the environmental benefits would be reduced by this factor, even though, the energy consumption results and GHG emissions for pyrolysis process in both scenarios differences are minimum.

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## VI. Appendix

### Appendix A. Kinetic constants

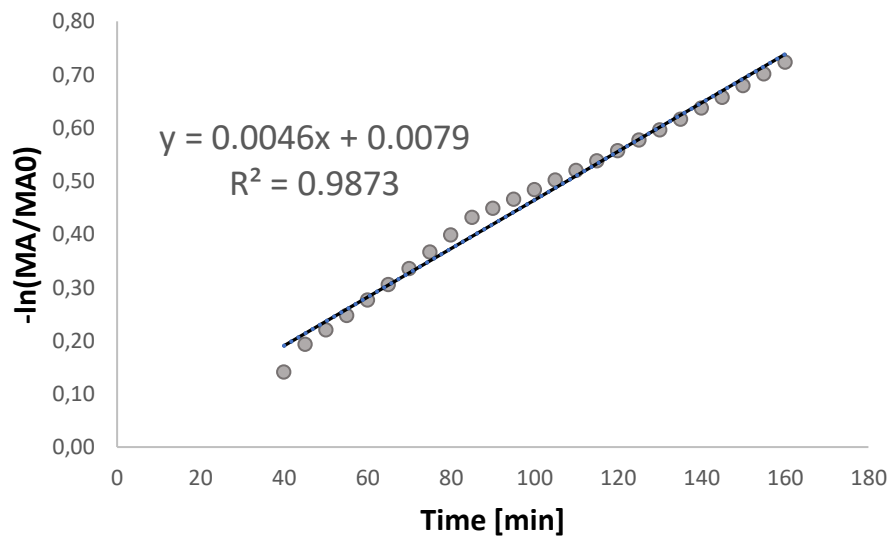


Figure A1. Kinetic constant for thermal cracking

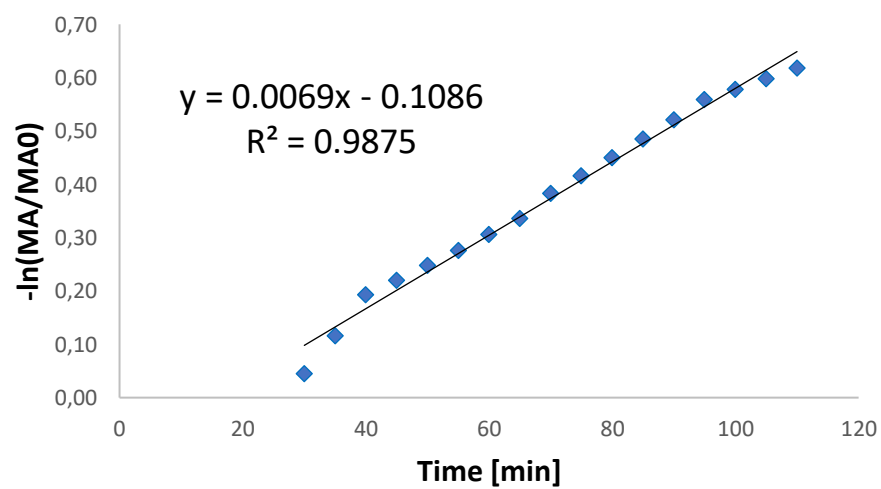


Figure A2. Kinetic constant for RH catalytic cracking

## Appendix B. Waste motor oil availability

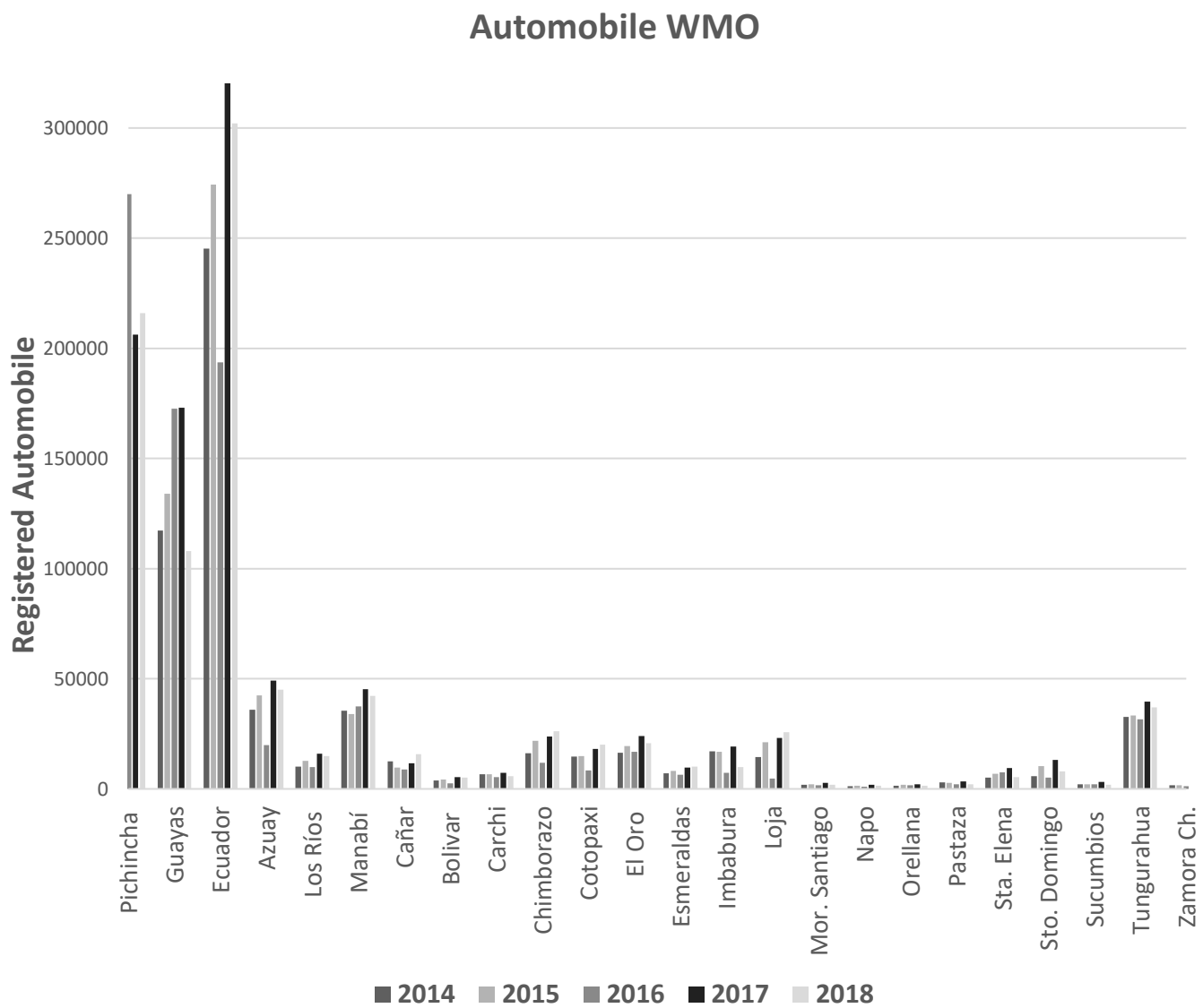


Figure B1. Registered automobile since 2014 to 2018 in Ecuador

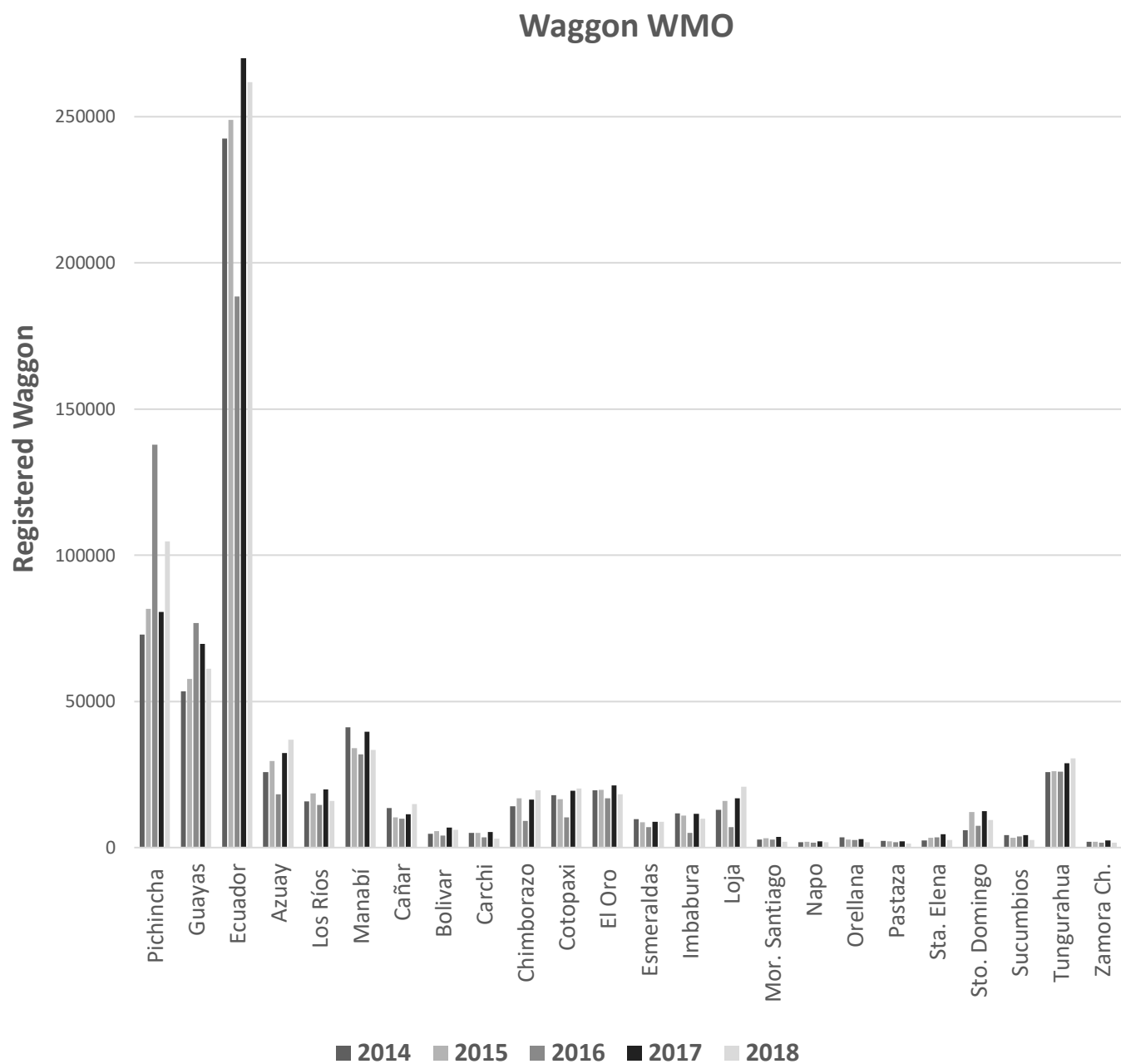


Figure B2. Registered wagon since 2014 to 2018 in Ecuador

## SUV WMO

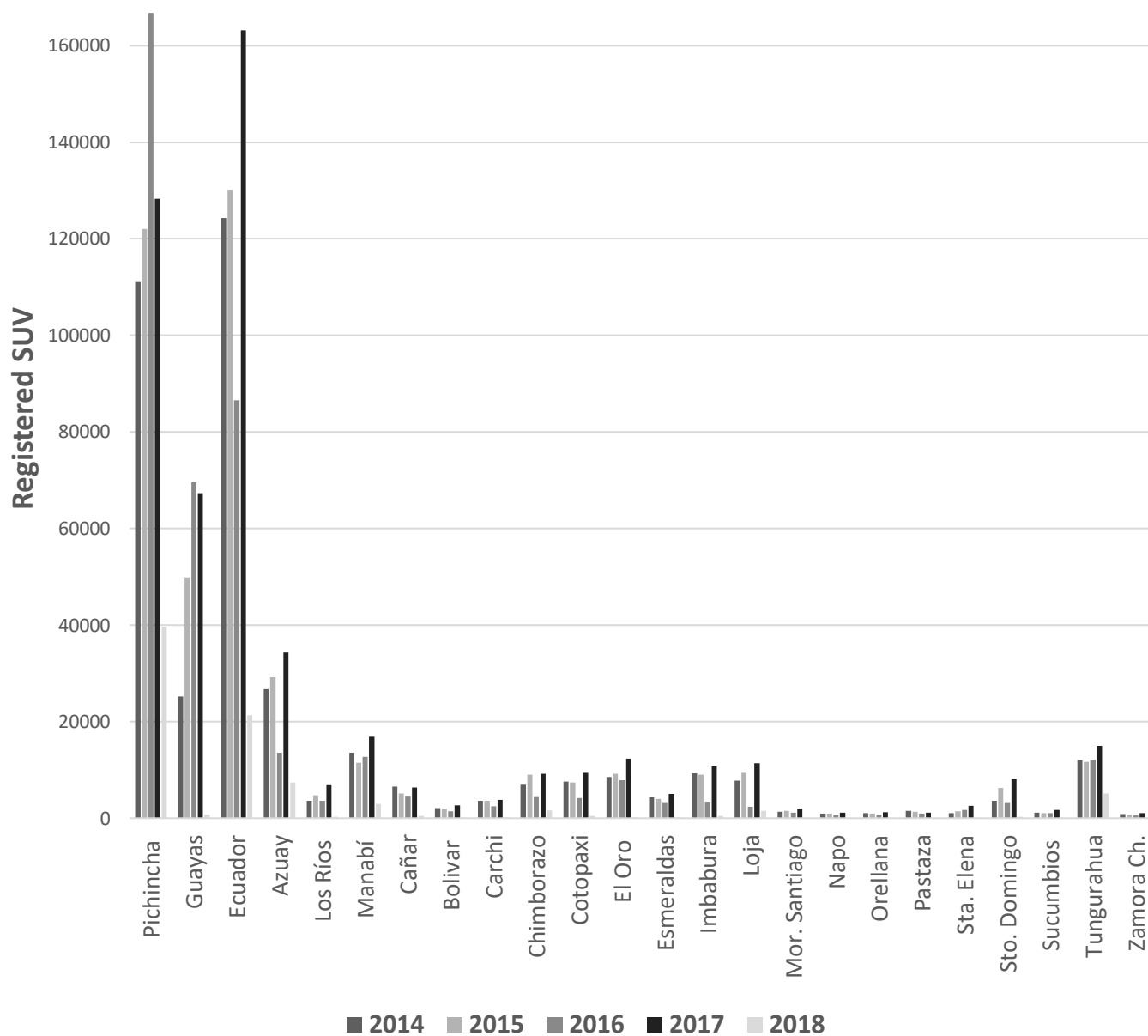


Figure B3. Registered SUV since 2014 to 2018 in Ecuador

### Appendix C. Rice husk availability

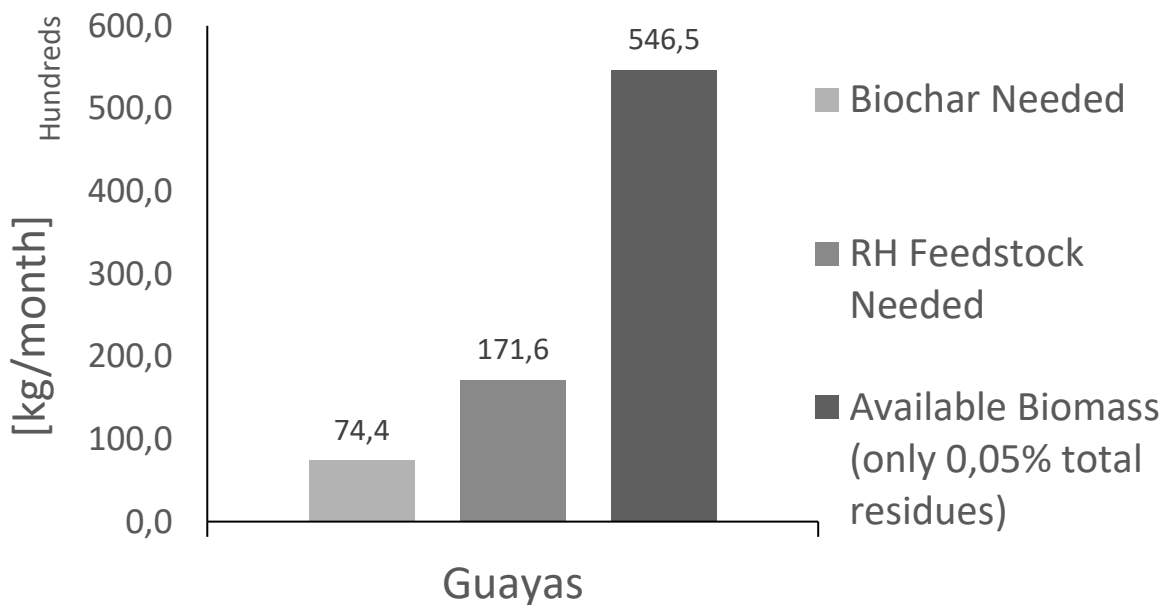


Figure C1. Rice husk availability for RHB production in scenario 1 using biomass from Durán, Guayas

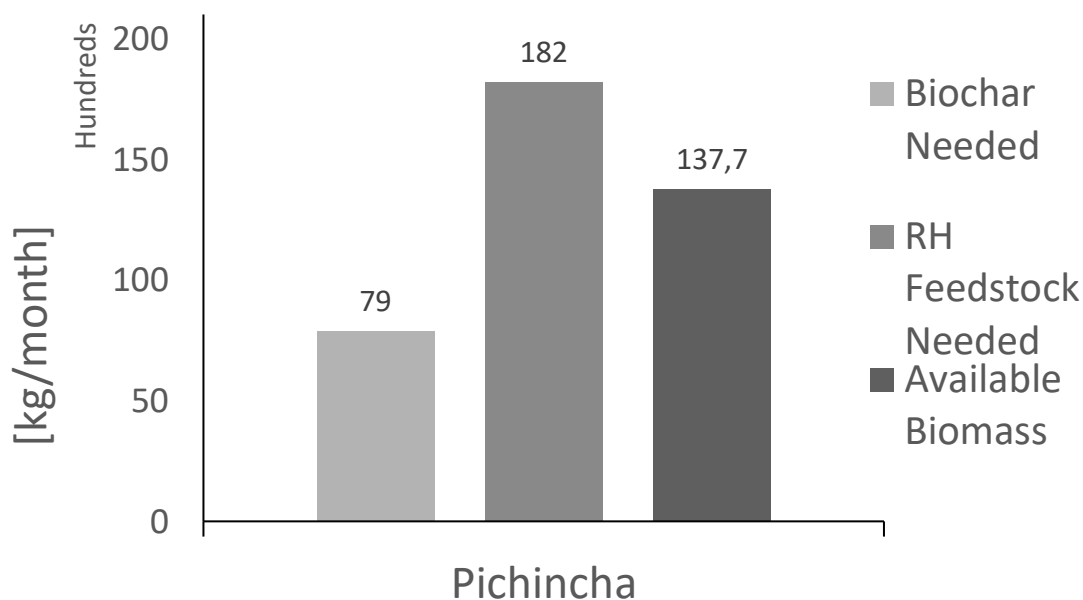


Figure C2. Rice husk availability for RHB production in scenario 2 but using biomass from Pichincha

## Appendix D. Carbon footprint calculations

Table D1. Estimation of the fuel consumption of the route for scenario 1

<b>Estimation of the consumption/route</b>	
<b>Estimation of specific fuel consumption</b>	
Specific empty diesel consumption [l.diesel/100 km]	24.31
Specific diesel consumption (l/100 kilometers) for the section	22.1300285
<b>ESFCR from the specific consumption</b>	
Diesel consumed in the section [l]	5.31120684
Diesel consumption without load [l]	31.50576
Open route fuel consumption [l]	36.8169668

Table D2. Estimation of energy consumption per shipment in scenario 1

<b>Calculation of Energy consumption and GHG per shipment (Guayas)</b>	
ET (Energy Consumption TtW) [MJ]	1321.72911
EW (Energy Consumption WtW) [MJ]	1572.08448
GT (GHG Emissions TtW) [kgCO <sub>2</sub> e]	98.3013015
GW (GHG Emissions WtW) [kgCO <sub>2</sub> e]	119.286973

Table D3. Estimation of energy consumption per shipping service in scenario 1

<b>Calculation of Energy consumption and GHG for shipping service (Guayas)</b>	
ET (Total Energy Consumption TtW) [MJ]	1321.72911
EW (Total Energy Consumption WtW) [MJ]	1572.08448
GT (GHG Emissions TtW) [kgCO <sub>2</sub> e]	98.3013015
GW (GHG Emissions WtW) [kgCO <sub>2</sub> e]	119.286973



Table D4. Estimation of the fuel consumption of the route for scenario 2

<b>Estimation of the consumption/route</b>	
<b>Estimation of specific fuel consumption</b>	
Specific empty diesel consumption [l.diesel/100 km]	54.23
Specific diesel consumption (l/100 kilometers) for the section	23.4658161
<b>ESFCR from the specific consumption</b>	
Diesel consumed in the section [l]	34.4947497
Diesel consumption without load [l]	430.47774
Open route fuel consumption [l]	464.97249

Table D5. Estimation of energy consumption per shipment in scenario 2

<b>Calculation of Energy consumption and GHG per shipment (Pichincha)</b>	
ET (Energy Consumption TtW) [MJ]	16692.5124
EW (Energy Consumption WtW) [MJ]	19854.3253
GT (GHG Emissions TtW) [kgCO <sub>2e</sub> ]	1241.47655
GW (GHG Emissions WtW) [kgCO <sub>2e</sub> ]	1506.51087

Table D6. Estimation of energy consumption per shipping service in scenario 2

<b>Calculation of Energy consumption and GHG for shipping service (Pichincha)</b>	
ET (Total Energy Consumption TtW) [MJ]	16692.5124
EW (Total Energy Consumption WtW) [MJ]	19854.3253
GT (GHG Emissions TtW) [kgCO <sub>2e</sub> ]	1241.47655
GW (GHG Emissions WtW) [kgCO <sub>2e</sub> ]	1506.51087