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Energy Potential of Agricultural and Forestry By-Products in Peru

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ABSTRACT

Reducing the demand for fossil fuels and the derived products can be achieved through the development of alternative energy sources. This work presents a countrywide study of the energy potential of lignocellulosic biomass sourced from agro-industrial by-products in the country of Peru. Ranking of the crops that produce the most waste was followed by an energy potential evaluation of carbohydrate conversion and thermochemical conversion. The crops with high calorific values were sugar cane bagasse, wood waste, and coffee husk. The energy potential of the principal lignocellulosic by-products, in terms of tons of oil equivalents per year, resulted from rice straw at 1.45 M, followed by corn residue at 1.13 M and sugar cane residue at 1.10 M. The northern region of Peru generated the highest quantities of rice (straw and husk), banana (husk and rachis), and sugar cane (bagasse and straw) by-products and the southern regions generated the greatest quantities of quinoa residue, all of which could be used as raw materials for biofuels and aggregates for materials. These results indicate that theoretically, this readily available biomass could meet the country's energy demands while promoting sustainability and national energy security.

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1. INTRODUCTION

Non-renewable fossil fuels, such as coal, oil and natural gas, are currently the main source of energy for the development of public, private, and residential activities. As is well known, consumption of these high-energy fuels generates harmful waste products such as CO_2, greenhouse gas (GHG), NOx, one of the main components of smog, and SO_2, and the precursor of acid rain. Additionally, the International Energy Agency (IEA) predicts that worldwide oil and gas reserves will fall by up to 60 % by 2030 while energy demand will continue to rise. For example, the growth per capita energy consumption in the United States depletes their fossil-fuel reserves in approximately 10 years [1].

A biofuel is a type of renewable and green fuel, where its energy is derived from biological carbon fixation and can be a solid like wood, liquid like bioethanol and biodiesel, or gas like syngas [2]. Nonetheless, biofuels are considered an effective alternative energy source for decreasing GHG emissions [3]. The most common biofuels produced worldwide are bioethanol, biogas, and biodiesel. New options including biobutanol, biopropanol, and syngas are currently under study [4]. Potential sources of biofuels consist of natural vegetation, cultivated products like fast growing trees and other crops grown for energy, residues from other agricultural activities such as forestry and food production, as well as other by-product sources such as city, husbandry, and slaughterhouse waste [2].

In recent years, lignocellulosic biomass from forestry and by-products of crop production has been studied for efficient conversion into both renewable energy sources as well as fibers for composite material manufacturing [5]. This waste to biomass repurposing also occurs in the production of organic acids, absorbent materials, fertilizers, high oils, and fermentation products, all comprising important aspects of the bio economy [6]. As such, lignocellulosic biomass sources are considered important platforms to promote energy independence as well as rural development while indirectly helping to reduce the impact of greenhouse gases by fostering food security and process and environmental sustainability [7]. Lignocellulosic waste from the forest sector is most often used in the form of sawdust and chips and as a low-cost energy source in the form of pellets and briquettes [8-10].

On the other hand, the agricultural sector in Peru is one of the main contributors to the national Gross Domestic Product (GDP) and the economies of several regions are dependent directly on this sector. As both agricultural exports and domestic food demand grow, their waste residues will also grow. Currently, much of residual biomass is discarded, incinerated, or repurposed for compost, with a small fraction used as animal feed, fertilizer, and solid and liquid biofuels.

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The objective of this research is to assess the energy potential and development opportunities for the utilization of lignocellulosic biomass in Peru. The authors hypothesized that biomass feedstock agricultural by-products would be enough to cover the energy demands in terms of ethanol production and heating value. To this end, this study organized its framework as follows. The existing non-renewable and renewable resource energy matrix for Peru is presented, along with current and future projection levels of the agricultural production of crops that could generate useful by-products. A literature review of research on the use of lignocellulosic biomass in Peru is then presented, followed by the energy potential for each crop by-product in terms of Higher Heating Value (HHV). The next section covers chemical characterization of each individual crop by-product and its energy potential in theoretical bioethanol yield. Complementary tons of oil equivalent (TOE) of all the geographical regions is used as an indicator to rank them prospectively considering the availability of feedstock to produce energy.

2. METHODOLOGY

In order to verify the proposed hypothesis, the information resulting from the literature review in the Google Scholar database of the last 7 years and in university thesis repositories on the Internet is presented. Websites from governmental entities such as Ministry of Agriculture and Irrigation (MINAGRI) [11-14] and Ministry of Energy and Mining (MEM) [15-17] were surveyed in order to have national production data organized in tables in the next sections. Ethanol yield was selected to verify the quantity of cellulosic bioethanol that could be produced from agricultural feedstocks. Theoretical ethanol yield from the compositional cellulose (glucan in $mL.g^{-1}$) was calculated through this relationship: [(180 g of glucose/162 g of glucan) × (0.51 g ethanol/g glucose)] / 0.789 g ethanol per mL; assuming 100 % conversion [18]. Complementarily, the energy potential was calculated in terms of the tons of oil equivalent (TOE) that represents the enthalpy of complete combustion of fuel, including the condensation enthalpy [19]. This value is compared to the energy released from burning one ton of crude oil and is equivalent to 41.87 GJ or 11.63 MWh. Both ethanol and TOE (1 TOE = 41.868 GJ) were selected as representative biofuels for the transportation sector.

3. RESULTS AND DISCUSSION

3.1. The energy scenario in Peru

Today, the Peruvian energy matrix is caused by the non-renewable source of natural gas around 65 % in 2018 [15-17]. This year, for example, the national consumption was around 83×10^5 TJ [17].

According to projections by the Ministry of Energy and Mining [15], energy consumption will be three times greater in 2040, caused by transportation, industrial, and trade sectors [15].

Peru addresses this additional demand by taking advantage of the energy potential of their various biomass resources as other countries have done. Muhammad et al. (2019) [20] in Pakistan and Balat (2010) [21] in Turkey, among others, demonstrated that biomass could play a significant role in sustainably, meeting increased national energy demands.

According to the Peruvian Supreme Decree No 021-2007-EM, biofuels would be commercialized primarily as additives for diesel and gasoline. However, it is also possible to meet the economic demands and sustainable energy requirements of non-transportation activities. Interestingly, Liu et al. (2014) [22] found that a mix of policy and market incentives had a large impact on the type of bioenergy feedstock developed and subsequent GHG emissions reduction. Overall, they found that the use of biomass for electricity generation had a far greater GHG offset potential than its production for vehicle fuel. Already, some Peruvian agroindustry companies currently use sugar cane bagasse as feedstock for steam generators that produce electricity [16].

Additionally, biomass as an energy feedstock has a significant advantage over other energy sources as it can be converted into solid, liquid, or gaseous states. This flexibility, combined with how demand influences technological adaptation, can help further spur innovation in sustainable energy generation [23].

3.2. Peruvian agricultural production and potential generation of by-products

Peru maintains a varied agricultural sector across its coastal, mountainous, and tropical regions, with rice, coffee, and hard yellow corn crops covering the greatest area cultivated, as depicted in Figure 1 [13-24].

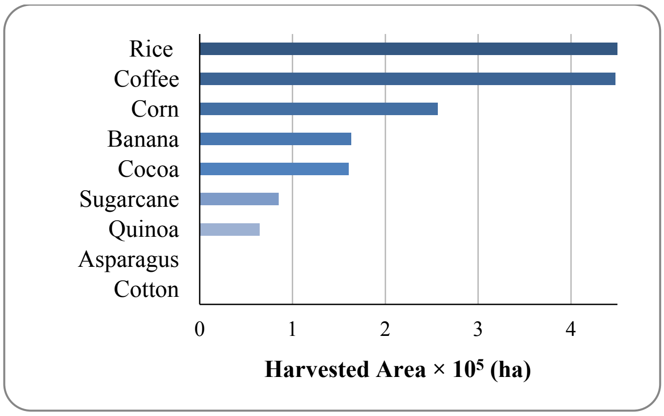

Figure 1. Crop-harvested area in 2018 of the main Peruvian agricultural products

Peru produces other important crops such as asparagus, cocoa, and quinoa which are the 5th, 9th, and 10th leading national agricultural exports by Metric Tons (MT), respectively. Peru leads the world as the largest exporter of fresh, preserved, and frozen asparagus, having the second-largest agricultural area under cultivation after China, and ranked third in yield (MT/ha) [25]. Interestingly, the regions of Ica and La Libertad produce 84.0 % of the area harvested and possible centers of innovation for derived products. With regard to genetic biodiversity, Peru accounts for 60.0 % of the biodiversity (genetic material) of cocoa and 50.0 % of quinoa [14], with Puno and Ayacucho having the largest harvesting area for quinoa.

Considering the harvested area, agricultural and forest residues were calculated in MT (Figure 2) [7, 26-29]. The straw from rice cultivation (4.27×10^6 MT), the stems and leaves from sugar cane (3.31×10^6 MT), and the stubble residue from corn (3.16×10^6 MT) generated the largest quantities of potential by-products in 2018.

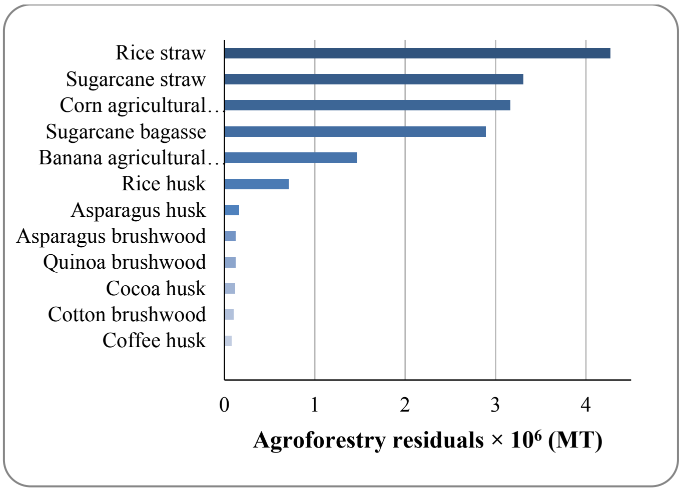

Figure 2. Generation of residuals from Peruvian of agroforestry in 2018

Focusing on 2018 and total crop by-products (MT), as well as listing Harvested Area (ha) and Production (MT) (Table 1), the two crops that generate the greatest quantities of potential residues are sugar cane and rice and are produced predominantly in the San Martin, Piura, and Lambayeque regions, while the third highest quantity of potential residues, corn, is predominantly produced both in the Ancash and Ica regions. It should be noted that sugar cane (bagasse and straw), rice (husk and straw), and asparagus (brushwood and straw) have two different by-products that comprise their total residuals.

Table 1. Crop area, production, and residues of the main crops (2018)

Product	**Harvested area (ha × 10^5)**	**Production (MT × 10^6)**	**Total Residues (MT × 10^6)**
Sugar cane	0.85	10.31	**6.20**
Rice	4.38	3.56	**4.98**
Hard yellow corn	2.56	1.27	**3.16**
Banana	1.63	2.19	**1.47**
Asparagus	0.31	0.36	**0.29**
Quinoa	0.65	0.10	**0.13**
Cocoa	1.60	0.14	**0.12**
Cotton	0.15	0.04	**0.10**
Coffee	4.47	0.37	**0.07**

According to the report "Renewables 2018 Energy Policy Network for the 21st Century", by 2025, Peru aims to have up to 60.0 % of total energy production provided by renewable energy sources including bioenergy [30]. In agreement, the “Peru Natural Gas Sector Report” in 2020 suggested that only 6.0 % of the potential energy from biomass had been utilized, which is a statistic that presents a substantial economic and sustainability opportunity [31].

In terms of the potential growth of national agriculture, The International Coffee Organization predicts that global demand for coffee will increase by 32.0 % by 2030, which can translate into an 87.5 % increase in Peruvian exports [32]. The International Cocoa Organization (ICCO) predicts that by 2023, global demand for cocoa will increase by 14.3 %. Peru has the potential to meet that demand as it is currently one of the top 10 worldwide cocoa exporters [11] and its production has been increasing at an average annual rate of 10.0 % over the past 13 years (2003-2015) [12]. Based on 2018-2020 figures, the world production of quinoa has a growth rate of 22.6 % and Peru, with an average annual market growth of around 13.0 %, could become the leading producer worldwide [13]. Finally, in 2018, Peru consolidated itself as the world’s leading exporter of asparagus (fresh and chilled), and given its two growing seasons and the historical trend of its annual export growth (2005-2015), it is expected to continue in that position into the future [33].

Given that the biomass residues of these crops will follow these growth patterns, their uptake could help contribute to the 60 % target of renewable bioenergy generation proposed in the Renewables 2018 Global Status Report [30].

Studies related to the reuse of lignocellulosic materials in Peru focused on alternatives such as material composites and bioethanol [34-37]. This review shows that no complete overview presents a countrywide evaluation of the energy potential of agro-industrial by-products in Peru. In response to this gap, the framework of the results will present prospective quantification of heat generation through simple combustion using indicators as Heating Value (HV) and tons of equivalent (TOE) by region. The attainable production of cellulosic ethanol production based on the composition of the lignocellulosic biomass (carbohydrates content) is discussed too.

3.3. Heating value (HV) of agricultural by-products

The energy contained in a lignocellulosic material can be measured in terms of calorific value during air combustion and expressed in kJ/kg or kcal/kg [19]. The accumulated plant biomass is not proportional to the energy absorbed during photosynthesis because the amount of the accumulated chemicals differs due to their distinctive energy densities [38]. This difference in carbohydrate generation depends on the species and stage of plant development and it can be characterized by the enthalpy of the complete combustion of a fuel, especially when all carbon is converted into CO_2, all hydrogen is converted into H_2O and is represented as the Higher Heating Value (HHV) [2].

Figure 3 shows the standard HHV values of the lignocellulosic by-products studied in this article, with sugar cane bagasse, wood waste, and coffee husk having the highest values of 4 600.0, 4 413.7, and 4 361.3 kcal/kg, respectively. In addition, the use of sawdust for the production of thermal energy has been studied in equipment such as steam generators, furnaces, and turbines due to their calorific value [20].

Beyond simple combustion, utilization of the heat capacity of biomass can also focus on the combination of technologies that would produce intermediate and final products. The production of coal and bio-oil by pyrolysis, gaseous fuels, and supercritical liquefaction are some other alternatives in thermochemical conversion [39-40]. Although studied since 1788, with the first patent registered by Robert Gardner, gasification and liquefaction are still in the research and development phases, approaching commercialization, with direct combustion and coal co-firing for electricity production projected as the most promising alternative [39, 41].

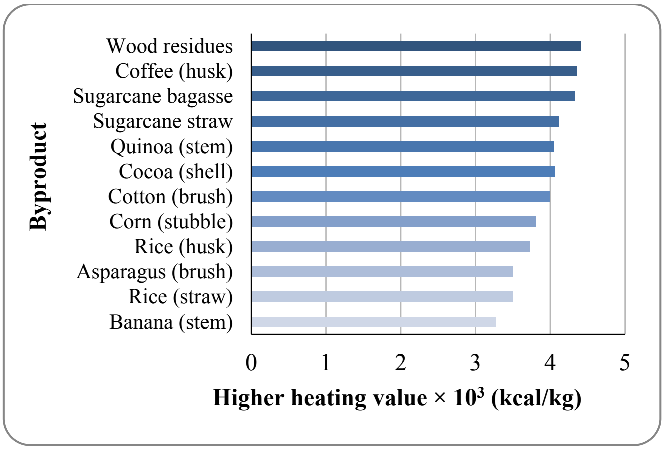

Figure 3. Higher Heating Value (HHV) of major Peruvian agricultural and forest residues

3.4. Characterization of agricultural by-products

To evaluate the energy potential of agriculture and agroforestry by-products, their chemical composition must be determined in terms of the percentage of phenolic content (lignin) and complex carbohydrates (cellulose and hemicellulose). An average composition, on a dry basis, would consist of cellulose (38-50 %), hemicellulose (23-32 %), lignin (15-25 %), and extractives (< 5 %), as reported in different studies corresponding to the principal Peruvian agricultural by-products, as shown in Table 2.

Of complex carbohydrates, cellulose is a polymer composed exclusively of glucose molecules bound by β-glucosidic bonds and hemicellulose is composed of heterogeneous polymers of pentose (xylose, arabinose), hexose (mannose, glucose, and galactose), and sugar acids; all these monomers of sugars can be used in fermentation processes to produce fuels [6, 43, 54].

Lignins are three-dimensional, complex, branched and amorphous heteropolymers formed from phenylpropane units (coniferyl, cumaryl, and synapyric alcohols) and have energy properties similar to those of solid fuels such as mineral coal [54, 55]. Their physicochemical characteristics are expressed by proximate analysis, elemental analysis, thermal stability analysis, and calorific value, indicating that they can be used for the production of thermal and electrical energy [5].

The research into the use and transformation of lignin is advancing rapidly. Using different physicochemical extraction procedures, lignin separated from their carbohydrates, and biomass fibers can have different structures, purities, and properties. According to Liao et al. (2020) [56], the three potential uses of lignin can be used for fuel synthesis, for biomaterial as macromolecules, and for pharmaceutical building blocks in aromatics.

In the first user group, lignin serves as a carbon source for energy production in the synthesized fuel. In the second user group, lignin functions in a macromolecular manner by taking advantage of their high molecular mass to produce adhesives, carbon fibers, and polymers including polyurethane foams. The third user group applies technologies to produce polymer building blocks and aromatic monomers such as benzene, phenol, vanillin, and toluene and xylene [57, 58].

The large amounts of lignin found in rice, sugar cane, and corn by-products represent a significant energy source that is currently underutilized in Peru. Lignin contents available from the most significant residues of rice straw, cane residue, and maize are 767 × 10^3 Mt, 1.4 × 10^6 Mt, and 696 × 10^3 Mt, respectively. Given an average calorific potential of 24 MJ/kg of pure and dry lignin, the energy potential amounts to more than 7 billion TJ. However, this biopolymer offers a variety of potential manufacturing routes in a biorefinery scheme and lignin is difficult to isolate and convert into chemical commodities, specialized chemicals, thermal and/or electric power, and advanced biofuels due to its chemical nature [4, 5, 56].

Table 2. Chemical composition of agricultural and agroforestry residues

By-product	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Reference
Rice (straw)	35.6	12.0	15.4	[42]
Corn (agricultural residue)	36.8	30.6	23.1	[43]
Sugar cane (straw)	39.8	28.6	22.5	[44]
Sugar cane (bagasse)	38.0	29.5	21.5	[45]
Banana (pseudostem)	38.5	25.4	5.8	[46]
Quinoa (agricultural residue: stem)	42.1	20.3	13.0	[47]
Rice (husk)	43.5	22.0	17.2	[48]
Asparagus (husk)	31.2	16.8	14.2	[49]
Cotton (bushwood)	37.9	20.4	25.0	[50]
Cocoa (peel)	18.6	13.9	14.2	[51]
Coffee (husk)	36.7	47.4	15.9	[52]
Wood residue: *Pinus patula*	36.6	25.0	28.5	[53]
Wood residue: *Eucalyptus camaldulensis*	45.0	17.9	29.5	[53]

3.4.1. Bioethanol yield

Bioethanol is an advantageous fuel used directly as not only an alcohol in specific engines, but also an additive to gasoline, as it cleans the combustion process, widens flammability limits, and increases octane, flame speeds, and vaporization heat [54, 59]. As such, the process of obtaining bioethanol is a highly studied technological transformation. One way to increase its production without increasing the planted area is to use the sugars of lignocellulosic biomass as a raw material in the fermentation process. The extraction of these sugars contained in cellulose and hemicellulose encompasses a sequence of stages from chemical pretreatment, chemical, or biological saccharification to conventional fermentation by yeast [43, 55]. While the glucose content to carry out such processes is found in cellulose, it should be noted that other sugars like xylose, an abundant component of most hemicelluloses, can also contribute to the production of bioethanol by using genetically modified yeasts that ferment both compounds [55].

As indicated in the methodology section, the theoretical yield for the production of bioethanol from each by-product was calculated considering the chemical composition of lignocellulosic residues, assuming that all the glucose contained in cellulose is used to produce ethanol. The raw materials with the greatest potential for conversion into ethanol are wood residue, rice husk, and quinoa stalk, yielding 23.0, 22.2, and 21.5 g bioethanol/g total cellulose, respectively as seen in Figure 4.

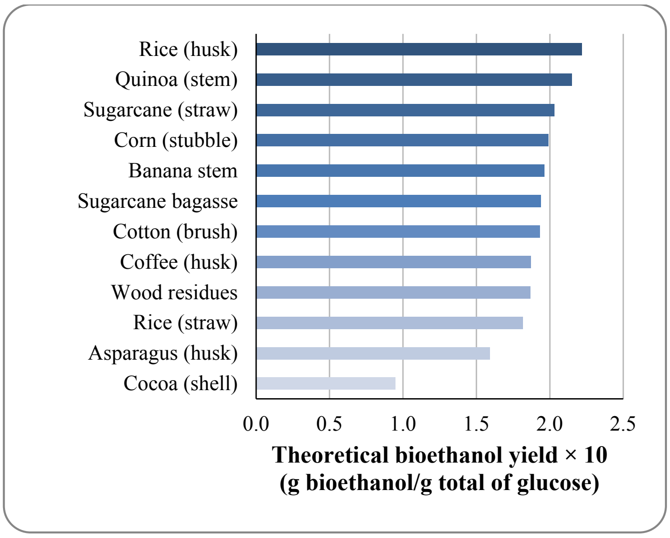

Figure 4. Theoretical bioethanol yield of major Peruvian agricultural and forest residues

In Peru, Peruvian Technical Standard restricts the ethanol content in gasohol to a maximum of 7.8 % and this ethanol is derived from corn (with higher CO_2 emissions than that made from sugar cane) [15-17]. It is demonstrated that lignocellulosic-derived ethanol leads to greenhouse gas savings [43, 54] relative to gasoline and corn ethanol; thus, its use represents an environmental positive impact for the nation.

3.5. Byproduct potential in TOE equivalent by region

Figure 5 shows the energy potential of the main lignocellulosic byproducts in terms of tons of oil equivalent (TOE) per year. As can be seen, rice straw (1.45×10^6), corn agricultural residue (1.13×10^6), sugarcane agricultural residue (1.1×10^6), and sugar cane bagasse (6.80×10^5) formed the classification.

To assess the geographical distribution of the energy potential, Figure 6 shows the distribution in TOE /year by region and biomass availability.

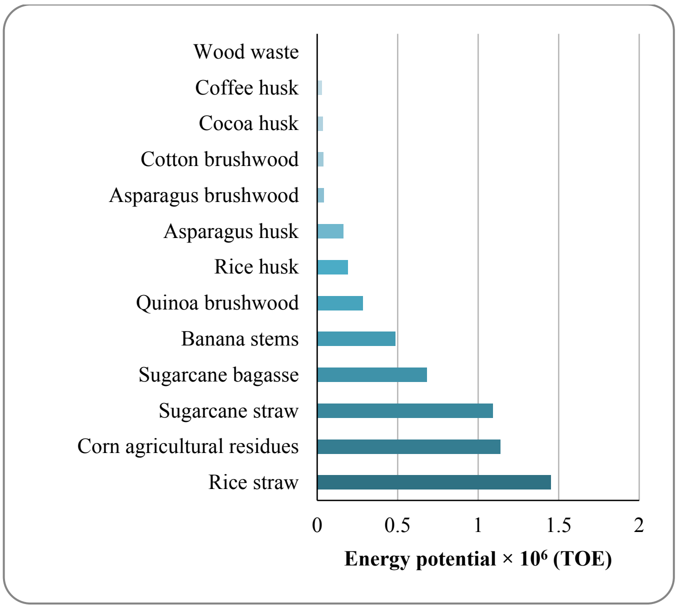

Figure 5. Energy potential (TOE) of major Peruvian agricultural and forest rresidues

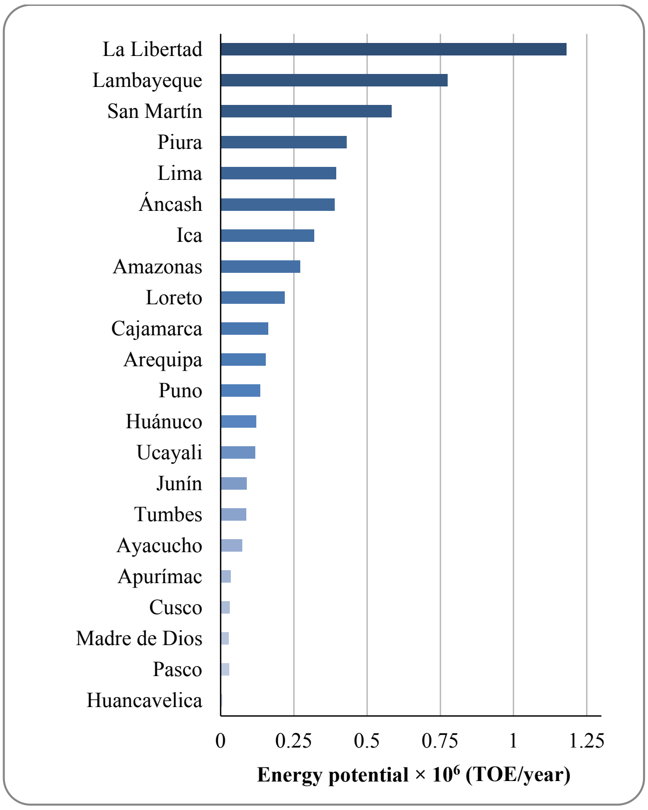

Figure 6. Energy potential (TOE) of Agricultural and Forest Residues by Region

The regions with the greatest energy potential are La Libertad (1.18×10^6 TOE), Lambayeque (7.74×10^5 TOE), San Martín (5.83×10^5 TOE), and Piura (4.29×10^5 TOE) localized in the north of Peru, as can be seen in Figure 7. Due to their location (400-2000 meters above sea level), these regions have tropical climates and landscapes of plains, which promote higher productivity per cultivated hectare and consequently increase the quantity of biomass feedstock for energy potential [60, 61].

Reference	TOE/Year	Main agroforestry residues
🟧	<10000	Rice straw, quinoa brushwood
🟫	100000- 170000	Rice straw, corn residues
🟦	170000 - 400000	Corn residues, sugarcane straw
🟨	> 400000	Rice straw, corn residues

Figure 7. Production of significant agricultural by-products in TOE/year and main agroforestry residues, by geographical region

4. CONCLUSIONS

In Peru, around 1.65 × 10^7 Mt of agricultural residues and 301 Mt of forest residues are generated annually. The northern region of Peru generates the highest quantities of biomass by-products, mainly rice (straw and husk), banana (husk and rachis), and sugar cane (bagasse and straw), which accounts potentially for more than 4 × 10^6 TOE per year. This value is equivalent to 20 % to the total national consumption; thus, their development could help reduce fossil fuel dependency, increase the energy security of Peru, and help guide other countries that share similar agricultural profiles.

5. ACKNOWLEDGEMENT

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