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Recent advances in residual biomass conversion into bioenergy and value-added products: A review of the Ecuadorian situation

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Últimos avances en la conversión de biomasa residual en energía y productos con valor agregado: Revisión de la situación ecuatoriana

Resumen

La biomasa residual es una materia prima clave para la producción de calor y electricidad, biocombustibles y productos químicos. Con base a los resultados reportados en la literatura, Ecuador, al ser una economía basada en la agricultura, tiene el potencial de satisfacer sus demandas energéticas cumpliendo con las regulaciones ambientales, mediante la conversión de biomasa residual autogenerada. En las últimas décadas, se han modelado y estudiado ampliamente métodos biológicos, químicos y termoquímicos convencionales a escala de laboratorio para la producción de biogás, bioetanol y otros combustibles sólidos y líquidos. Los cuales pueden convertirse en la piedra base para el desarrollo de aplicaciones a mayor escala. Además, estudios recientes, han mostrado también el desarrollo de nuevos procesos para la conversión de residuos de biomasa ecuatoriana en productos de valor agregado, tales como materiales porosos para tratamiento biomédico y de aguas residuales, producción de hidrógeno, entre otros. Esto, en general, proporciona un ciclo de revalorización de las corrientes de residuos actuales, reduciendo el problema del tratamiento y eliminación de residuos, con el objetivo de introducir productos para el desarrollo de una bioeconomía local sostenible.

Palabras clave: Biomasa ecuatoriana, biomasa residual, agroindustria, bioenergía

Abstract

Residual biomass is a key feedstock for the production of heat and electricity, biofuels, and green chemicals. Based on results reported in the literature, Ecuador, an agriculture-based economy, has the potential of meeting its energy demands while satisfying environmental regulations, by the conversion of self-generated residual biomass. Conventional biological, chemical and thermochemical methods have been modeled and widely studied at laboratory scale for the production of biogas, bioethanol, and other solid and liquid fuels. Based on that, they could become a milestone for upcoming scaled-up applications. Moreover, recent studies, have also shown the development of

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new processes for the conversion of Ecuadorian biomass residues into value-added products for future applications, such as porous materials for biomedical and waste water treatment, hydrogen production, among others. This, in general, provides a revalorization cycle of current waste streams, reducing the problem of waste treatment and disposal, and aiming to introduce bio-based products for the development of a local sustainable bio-economy.

Keywords: Ecuadorian biomass, biomass residues, agroindustry, bioenergy

INTRODUCTION

Fossil fuels, such as crude oil, coal and gas remain the major sources for world energy supply. Proven reserve projections show that fossil sources would certainly expire, considering the current growing consumption rate [1-3]. Thus, the existing energy supply system appears unsustainable not only due to reserves depletion, but also implementation of more rigorous mandatory environmental regulations [4; 5]. Thus, driving worldwide research efforts into renewable sources of energy for gradually replacing fossil fuels [6]. Among other alternatives, biomass used for bioenergy production is a potential candidate for partially meeting the energy demand and reaching the net zero CO_2 emissions to the atmosphere [7]. However, bioenergy from first generation biomass, also used as a food source, at industrial production might accelerate deforestation and desertification, trigger possible water privation, and would considerably increase food prices [8; 9]. Thus, biomass residues, known as second generation biomass, which also include those available at farms, released in the agro-food industry, and those remaining after product use, have grown in importance for bioenergy production. Some developed countries have already established systems to use millions of tons of organic wastes from agricultural, municipal, and industrial processes [10; 11]. Meanwhile, emerging nations have not shown the same degree of development. It is estimated that about 45% of waste generated in Latin-America ends up in open-air dumps or watercourses [12-14].

In particular, Ecuador, as many other countries in Latin-American, has an agriculture-based economy. Its geographical location provides multiple micro-climates from tropical to cold, allowing a large diversity of agricultural products. Thus, residues from agriculture, livestock farming and forestry represent important amounts of biomass. Accordingly, rice, banana, cocoa, coffee, sugarcane, maize, palm oil, plantain, pineapple, and palm heart crops represent the 84% of the total Ecuadorian agricultural production, generating about 79% of the total permanent biomass residues [15; 16]. As depicted in Figure 1, biomass residues are mainly concentrated in 5 Provinces (El Oro, Esmeraldas, Guayas, Santo Domingo) with high residue location density of approx. 200 ton km^{-2} $year^{-1}$, and Los Ríos generating as much as 700 ton km^{-2} $year^{-1}$. Ecuador's potential for producing bioethanol, biodiesel, biogas or other energy carriers from biomass has been widely demonstrated. Being enough to drive the country towards the implementation of a future circular economy [17-21]. For instance, just the Ecuadorian palm oil sector generates nearly of 6.8×10^6 tons $year^{-1}$ of residual biomass, which include, mesocarp fibers (3.1×10^8 kg $year^{-1}$), kernel shells

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(KS) (1.2 x 10^8 kg year^{-1}), empty fruit bunches (5 x 10^8 kg year^{-1}), and field waste (5.9 x 10^9 kg year^{-1}) [16; 22]. (For a complete report about the Ecuadorian biomass production and potential, please refer to [16]). Even though most of the residual biomass could be used as value-added feedstock, bio-based chemical precursors or renewable energy sources, most of these residues remains underutilized. This waste can also contribute to contaminate soils and water source and the generation of greenhouse gas (GHG) emissions, due to uncontrolled degradation. As listed in Figure 2, there are several causes for biomass underutilization, according to several authors [23-25].

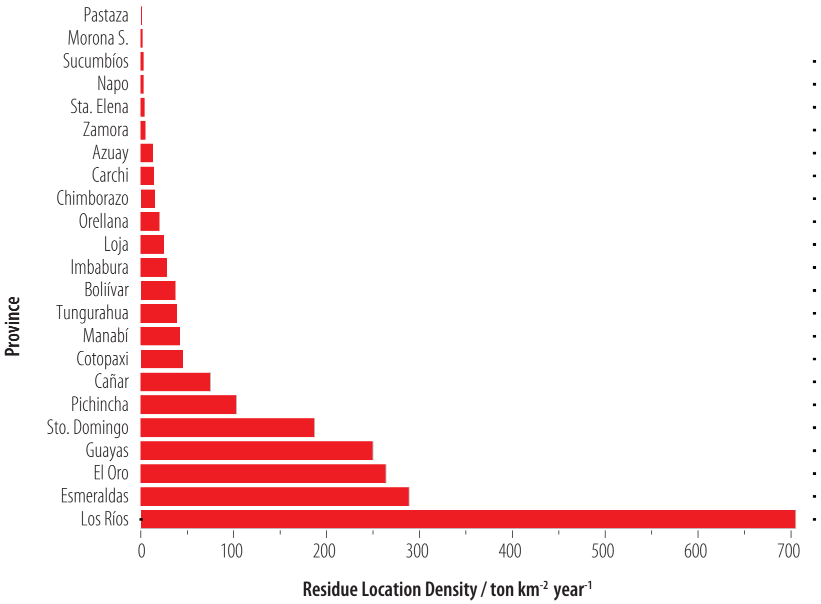

Figure 1. Ecuadorian biomass residues produced per location. Data from [15]

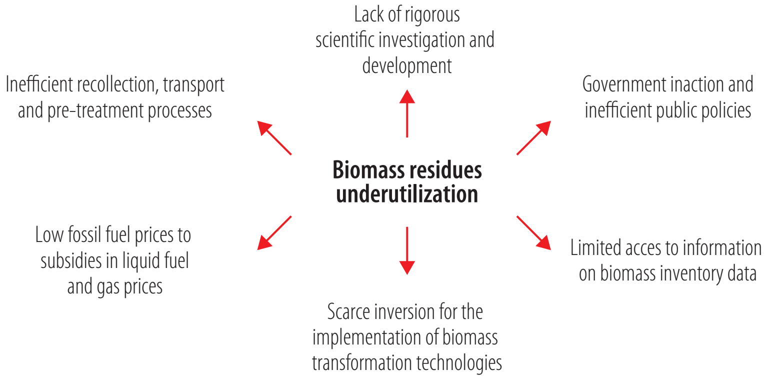

Figure 2. Major causes for biomass underutilization, according to several authors [23-25].

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As already mentioned, in Ecuador, the management and use of biomass for bioenergy production is still limited [26]. For example, a recent study showed that the application of thermo-chemical processes (e.g. direct combustion, gasification coupled with gas turbine, pyrolysis, among others), just using banana residues, could provide around of 650 GWh of energy [27]. However, by 2018, sugarcane bagasse, residues from oil palm processing, and residues from the wood industry, contributed only to 1.8% (≈400 GWh) of the total nation's electricity generation via co-generation systems [28-31]. Other initiatives, for producing ethanol, biogas, and biodiesel from sugarcane, pineapple, naranjilla (*Solanum quitoense*), and palm and Jatropha (*Jatropha curcas*) oil mills, respectively, have been developed without a considerable representation on the energy system [32-34]. Altogether, there are still scarce studies not only for bioenergy generation, but also for creating products with value-added applications.

Therefore, this contribution aims to review (see scheme in Figure 3), recent studies concerning not only the biological (anaerobic digestion, alcoholic fermentation), and thermochemicalambustion, gasification and pyrolysis) conversion of Ecuadorian residual biomass, but also the new approaches for producing value-added products for future applications. Searches were performed in a database and a search engine, such as Elsevier and Google Scholar, respectively. Eight search items were developed based on the scope of this study (e.g. "residual or recovered biomass AND Ecuador AND anaerobic digestion"). To be included, the papers had to meet a set of eligibility criteria: i) studies must have used Ecuadorian biomass, and should have been published in the last decade.

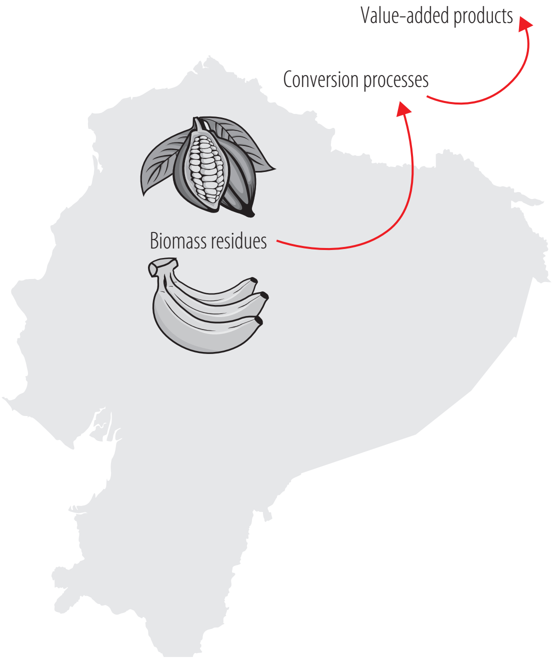

Figure 3. Schematic representation of the methodology followed in the short-review.

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BIOLOGICAL CONVERSION

Anaerobic digestion

Biogas might be the most promising renewable source for addressing global energy demands and providing environmental benefits. It is a mixture of mainly methane and carbon dioxide CO_2 that can be produced by anaerobic digestion (AD), which involves: i) microorganism hydroxylation of organic material into sugars, monoacids, and fatty acids under anaerobic conditions (step 1 in Figure 4), and ii) fermentation of hydrolytic products into a gas effluent (steps 2-4 in Figure 4). Benefits such as low sludge production, simple technology application and low energy consumption, make AD an efficient technology for the treatment of organic waste [35; 36]. In the Ecuadorian scenario, biological conversion can be by far, the most studied process for energy generation; however, its application has been delayed due to low-cost traditional technologies (i.e. hydroelectric power), and lack of research and economic incentives [21; 37; 38], among others.

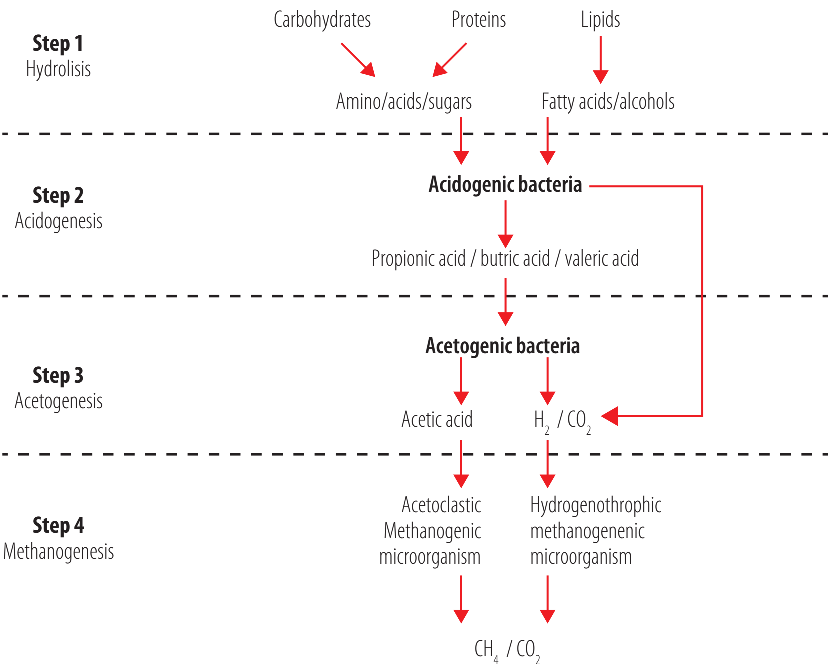

Figure 4. Biological degradation steps in anaerobic digestion. Based on [51].

Lately, some efforts have been done to show the potential of anaerobic mono-and co-digestion of the organic fraction of municipal solid waste (MSW) (sediments and fruit and vegetable wastes from markets) [39-42], manure residues (e.g. bovine, pig, hen, sheep excrements) [43-46], and biomass recovered from agro-industrial wastes (blackberries, avocado, soybeas, sugarcane, cocoa, plantain, banana, among many others) [47-50]. MSW and manure residues have been commonly studied in co-digestion processes at lab-scale reactor designs, aiming to be milestones for the design and implementation of pilot-scale prototypes for energy generation in cities and small farms. Even though co-digestion shows higher biogas yield and selectivity into methane production compared with mono-digestion, further investigation is still required to understand how AD process parameters could influence the overall methane production, necessary for scaling-up projects.

In this sense, studies of mono-digestion have given insights to better understand AD process of Ecuadorian agro-industrial wastes. Almeida-Streitweiser [51] developed a complete kinetic investigation for understanding the dependency of variables, such as feed composition, fed load rate, residence time and process temperature of the rate of biomass degradation. Applying a simplified power law model, a mean reaction order of 3.7 was obtained. Interestingly, it was demonstrated that there was a different rate determining step if the system works at mesophilic (20-40 °C) or thermophilic (50-60 °C) temperatures, respectively, due to shifts in the activation energies. Furthermore, it was shown that a different biological degradation mechanism (acetoclastic or hydrogenothropic methanogenesis) governed the process, depending on the reaction temperature (see step 4 in Figure 4). In a later study, Almeida-Streitwieser and Cadena Cabezas [47], further showed the dependence of biomass composition (sugar, lipid, protein and fiber content) in relation to biogas production and quality. The highest biogas production was observed for biomass with higher protein content (soybean feedstock), while highest methane content was related to bigger amounts of fiber in the structure (sugarcane bagasse substrate). That study also showed the correlation between pH value and volatile fatty acid concentration of the reactive mixture with the biogas production and composition. Similarly, Acosta *et.al* [48], showed that cocoa residues, which are rich in lignin but lack of essential nutrients, could struggle to maintain the methane production (conversions up to 50% with a 60% methane content) and a balanced pH in long-term reactions. Thus, cocoa residues might need special pretreatments and the application of co-digestion methods with nutrient-rich co-substrates in order to optimize energy production and enhance its application. Finally, biomass storage incidence, before AD, using Jatropha seed cake as feedstock, have been addressed by Gavilanes *et al* [49]. They showed that different times of biomass storage with water could control the amount of biogas and its quality. *Jatropha* cake stored for 18 months revealed to be more efficient than a cake stored for 6 months for biogas production, but with a lower selectivity towards CH_4.

Alcoholic fermentation

Globally, nearly of 50% of total energy demand is consumed in the form of liquid fuels. Thus, bioethanol production has been identified as a viable short-term solution to reduce crude oil consumption and environmental pollution, as it can be used in low blends with gasoline without engine modification. Among other methods, bioethanol can be produced primarily from fermentation processes of biomass from agricultural and forestry residues with high sugar or starch contents [52; 53]. In Ecuador, residual biomasses like banana, *Jatropha curcas,* Andean tubers, sugarcane bagasse, pruning waste (e.g. from *Ficus benjamina*, *Euphorbia laurifolia*), and others

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have been lately successfully studied as feedstocks for bioethanol production [54-62]. For a complete overview of research and perspectives for second generation ethanol production from Ecuador residual biomass in earlier years, please refer to the work of Carvajal *et al*. [63]

Lately, some studies have assessed the potential of second generation ethanol from banana wastes [54; 55]. In the first approach, theoretical calculations were developed to estimate the conversion efficiency. Banana residues from different sources located at 440 m asl (medium-size organic banana farms) and 26 m asl (small-scale banana producers) yielded a net-energy balance of 17.1 and 7.2 MJ l^{-1}, avoiding carbon emissions of about 0.44 and 0.34 kg l^{-1}, respectively. These results, showed the effect of cropping at different altitudes over bioethanol generation. It has also been identified that bioethanol production from sugarcane represent a huge opportunity of development for small communities in the rural area. Velazquez-Marti *et. al* [56] developed a complete model to predict performance and product quality of production of bioethanol based on Brix grades during the bio-fermentation of cane juice with *Saccharomyces cerevisiae*. According to the authors, this prediction method could importantly reduce costs compared to common methods of control, as it is not sensor based, making the process affordable in economically depressed areas.

On the experimental side, a few studies have addressed the benefits of applying different biomass pre-treatments and biomass conversion methodologies (see summary in Table 1). Bonilla *et al.* [57], addressed a complete kinetic study for the successfully production of bioethanol (7% v/v yield) from ripe banana peels, which were discarded from the production lines of the company Diana Food S.A. in El Oro province. The kinetic study showed the positive effect of adding polyethylene glycol for degrading the inhibiting compounds present during the enzymatic (conidia of the *Trichoderma viride* fungus) hydrolysis of the substrate, before alcoholic fermentation with a commercial active dry yeast (*Saccharomyces cerevisiae*). Moreover, Costa *et al.* [58] have shown eight different chemical pretreatments for lignin degradation as alternative of physical-mechanical methods, before enzymatic saccharification of rachis from banana cultivated and collected in Guayas province. Above others, hypochlorous acid showed to be the most effective agent for lignin removal; thus, obtaining the most promising cellulose-to-glucose conversions. Portero-Barahona *et al*. [59] have also shown a combined pretreatment using sulfonate, TiO_2 and alkali microwave irradiation for lignin degradation prior enzymatic saccharification of sugarcane bagasse obtained from a sugar production company in Imbabura. Pretreated feedstock showed an increase of the total reducing sugars and saccharinic acid production in about 5 and 33% compared to just microwave irradiation in water, respectively. Nevertheless, this process might present cost and environmental problems when used industrially. Finally, a complete study comparing the bioethanol production potential of starches from three Andean tubers (*Solanum tuberosum, Manihot esculenta, Ipomea batatas*) has been recently released. That study showed that the starch source does not affect significantly the amount of sugars obtained after the enzymatic digestion process; thus, it does not affect the bioethanol production during fermentation. Interestingly, the simultaneous saccharification/fermentation process proved to be a more suitable process for ethanol production compared to sequential saccharification and fermentation [62].

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Table 1. Summary of bioethanol production studies from residual biomass applications.

Biomass	Source/ location	Special treatment	Enzyme	Highlights	Ref.
Banana peels (Cavendish variety)	Diana Food S.A./El Oro	Polyethylene glycol inhibitor prior enzymatic hydrolysis	*Trichoderma viride* Conidia	7% v/v bioethanol yield	[57]
Rachis from banana plants (*Musa paradisiaca var. barraganete*)	Guayas	Chemical pretreatment for lignin degradation (e.g. sodium hypochlorite, hypochlorous acid, hydrogen peroxide, alkaline hydrogen peroxide, and combinations)	Cellulase and beta-glucosidase	> 80% delignification yield	[58]
Sugarcane bagasse	Ingenio azucarero del Norte/ Imbabura	Sulfolane, TiO2 and alkali microwave irradiation prior enzymatic saccharification		15.24 g L^{-1} production of saccharine acids	[59]
Potato (*Solanum tuberosum*), cassava (*Manihot esculenta*), and sweet potato (*Ipomea batatas*)	-	-	*S. cerevisiae*	> 90% Ethanol Yield for sweet potato in a simultaneous saccharification-fermentation process	[62]

THERMOCHEMICAL TRANSFORMATIONS

Thermochemical transformations can be applied to any type of biomass, including agricultural and forestry residues, by-products from the food industry, organic municipal wastes, etc. Thermochemical conversion technologies mainly include combustion, gasification and pyrolysis. During combustion, biomass (organic material) is burnt in excess air to produce heat. It is the easiest and most proven technology for power generation. However gasification, its overall heat to power efficiency is low. Gasification, on the other hand, usually occurs at high-temperature environments in the presence of oxygen or other oxidants, such as carbon dioxide or steam. It has many advantages over combustion, as it can use low-value feedstocks and convert them into electricity and transportation fuels (e.g. syngas) [64; 65]. Lastly, pyrolysis enables the production of liquid, gaseous, and solid fractions (e.g. bio-oil, pyrolysis gas, biochar) by adding heat to the feedstock in absence of oxygen. Depending on the pyrolysis and the technology applied, high thermal efficiency and low NO_x, SO_x, CO_2 emissions can be obtained [66-68].

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This contribution has identified several works addressing the potential of thermochemical transformations over different types of residual biomasses, such as avocado, carob (*Ceratonia siliqua*), mango, neem, bananas, teak pruning, and mannan-rich ivory nuts (for more information please refer to [69-71]). However, *Jatropha curcas* (see Table 2), and palm oil residues have received more attention. On the one hand, *Jatropha curcas* seed cake (JCSC) (i.e. residue from *Jatropha curcas* fruit oil extraction process) has been assessed as an interesting option for energy production (see process at Fig. 5a). In an early study, the obtained results from the microwave pyrolysis of JCSC indicated that the remaining organic liquid substances (bio-oil), the solid products (biochar), and the gaseous fraction are still potential energy sources that can be exploited. For instance, the liquid effluents (gross calorific value ≈) showed a maximum content of potential liquid fuel substances of around 75 %. In particular, this bio-oil might be considered as a source of liquid fuel for Otto-cycle engines. Nevertheless, it might need a distillation process to isolate the potential liquid fuels from water formed during pyrolysis, revealed by low gross calorific (3.37 MJ kg^{-1}) and bulk density values (1.09 kg m^{-3}). Moreover, the solid product revealed a high gross calorific value close to 28.30 MJ kg^{-1} that could be further applied for energy generation by combustion [33].

Table 2. Summary of *Jatropha curcas* residual biomass applications.

Biomass	Special treatment	Biomass Calorific value (MJ kg^{-1})	Use	Products	Reference
Jatropha curcas seed cake	-	18.62	Microwave pyrolysis	Bio-oil	[33]
Jatropha curcas seed cake	-			Biochar	
Jatropha curcas	Pelletized with wood chips	19.96	Combustion	Gas effluent (CO, CO_2, O_2, Hydrocarbons)	[72]
Jatropha curcas seed cake	Pelletized with peel of Jatropha curcas shell	22.14	Combustion	Gas effluent	[73]
Jatropha curcas	Pelletized with pruning residues	-	Combustion	Gas effluent	[74]

In this sense, Rivadeneira *et al*. have pioneered the use of biochar pellets from residual biomass as combustion fuel [72; 73]. In a first approach, pellets from *Jatropha curcas* combined with wood chips (25-75 wt%; calorific value ≈20 MJ kg^{-1}) were successfully tested in a small prototype horizontal burner (60 kWh) coupled to a combustion chamber. However, further investigation is needed, as CO emissions were relatively high compared to those observed during combustion of other types of biomasses in the

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same equipment (2.34 and 0.019 vol%, respectively). Seed cake biochar (SCB), which was obtained by the pyrolyzed residues resulting from Jatropha nut oil was combined with the peel of the fruit of the same plant (*Jatropha* shell (JSh)) to form pellets (see complete process in Figure 5 a and b). Those pellets were also tested in a semi-industrial continuous burner with a horizontal combustion chamber. Pellets of 4 mm particle size composed of equal amounts of JSh and SCB showed the greatest mechanical stability and higher heating values (≈ 22.14 MJ kg^{-1}). An economic assessment for the most successful solids stated the commercial viability of this type of biochar. Their energy cost (around 0.005 USD MJ^{-1}) represented just one third of the energy cost if using LPG for energy generation. However, according to Heredia-Salgado *et al*. [74], the above mentioned pellets suffered from high ash concentration content during combustion, which promoted instabilities on the flame and extinction of the combustion process within 14 minutes. Thus, in this recent publication, the authors studied a 25 wt % *Jatropha curcas* pellets with 75 wt % of pruning residues as more efficient fuel, which showed a stable flame and a sustained combustion process (> 60 min). Even though, the positive results, further investigation (e.g. biomass pre-treatment, better burn equipment) is still needed to improve the combustion process, and reduce the related CO emissions.

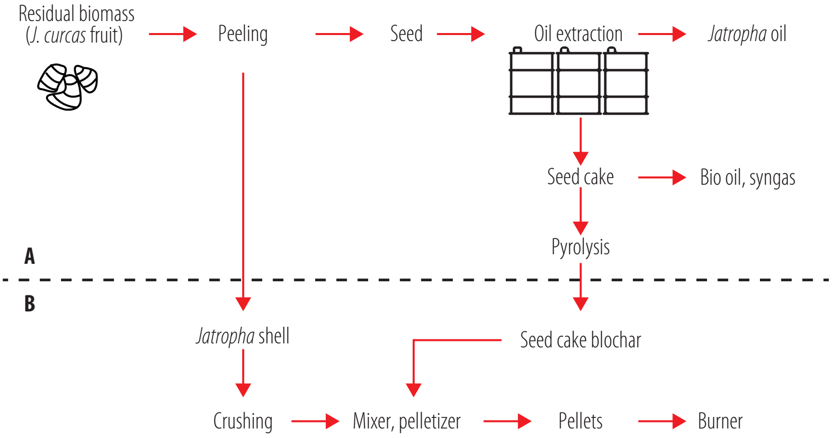

Figure 5. Biomass residue valorization scheme from a *Jatropha* oil extraction plant. a) Common process of pyrolysis of *Jatropha curcas* fruit residues, and b) further physical treatment (pelletization) for energy production via combustion. Based on [73].

On the other side, the technical and economical utilization of Palm oil kernel shell (KS) biomass residues as solid fuels for energy purposes have also been widely addressed [22; 75]. Accordingly, it was demonstrated that the replacement of diesel by untreated KS would reduce in eight times the fuel cost of a thermal energy production in a burner, with CO gas emissions below the limits stablished by European standards (260.1 and 500 mg N^{-1} m^{-3}, respectively). Moreover, if the right tax policies (e.g. non subsidies for diesel) and incentives for renewable production were implemented, associated production infrastructure would be recovered in four years. Palm oil KS biomass residues have been also studied as feedstock to produce both thermal energy and biochar (see Fig. 6a) [76]. An auto-thermal prototype modular auger reactor (i.e. neither diesel nor natural gas was used for initial heating) was used to produce macro-porous biochars with pore radius

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between 0.42 to 12.48 μm and ash with potential soil nutrients, such as silica, potassium, and phosphorous. Recently, KS residues have been also valorized together with mesocarp fiber, which are the most abundant residues on palm oil mill plants, in a complex pyrolysis and torrefaction combined process (see Figure 6 a and b) to produce biochar and torrefied fuel [77]. It was observed that the integrated process starts to be auto-thermal at 460 °C with an average energy efficiency of 60%. Thus, the pyrolysis and torrefaction process could represent an alternative to valorize residual biomass in the palm oil sector.

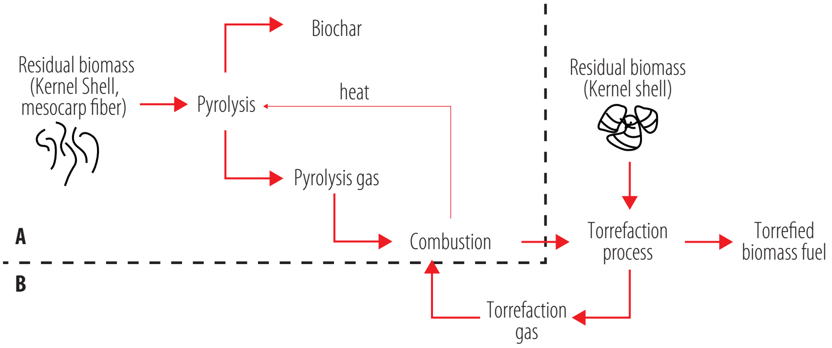

Figure 6. Scheme of a combined pyrolysis and torrefaction process for valorizing mesocarp fibers and kernel shell residues from a palm-oil small mill. Based on [77].

VALUE-ADDED PRODUCTS AND FUTURE APPLICATIONS

Hydrogen production

In the near future, it is expected that energy supply will be satisfied by regions with high potential for renewable generation. For instance, many research groups have shown the technical and economic feasibility of importing energy from Northern Africa to Europe [4; 78], taking advantage of the already installed fossil fuel infrastructure (e.g. ships, pipelines, gas stations) for transporting and commercializing the so-called liquid organic hydrogen carriers. Hence, the worldwide hydrogen e-fuel synthesis and use appears as the most probable solution for meeting local and global energy demands [79]. Even though no experimental methods for hydrogen synthesis could be found during the present review, a few publications have shown the Ecuadorian potential for hydrogen synthesis and energy generation from residues. According to Posso *et al.*, municipal solid waste-derived hydrogen generation could follow two paths: i) gasification combined with steam reforming, and ii) gasification combined with electrolysis. According to the authors, being the first method the most effective, with a theoretical national production of H_2 of 265,056 tons year^{-1}. They estimated that MSW-derived H_2 could satisfy public transportation energy demand in 91% of the country. In fact, the three largest urban centers (Guayas, Pichincha, Azuay), which produce around 57% of the total national MSW, could easily replace their local urban transportation diesel demand [80; 81]. In a later publication, Posso *et al.* [15] evaluated Ecuador's residual biomass sources as raw material for hydrogen production, highlighting its uses not only as energy vector, but also as input in manufacturing processes (e.g. oil refining, fat hydrogenation and urea

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production). The total amount of possible H_2 production was calculated in approx. 1.6 x 10^6 tons year^{-1} (see Figure 7), applying different conversion paths, such as gasification, combustion & electrolysis, and bio-methanization and reforming, which represented 38% of the national demand in 2017.

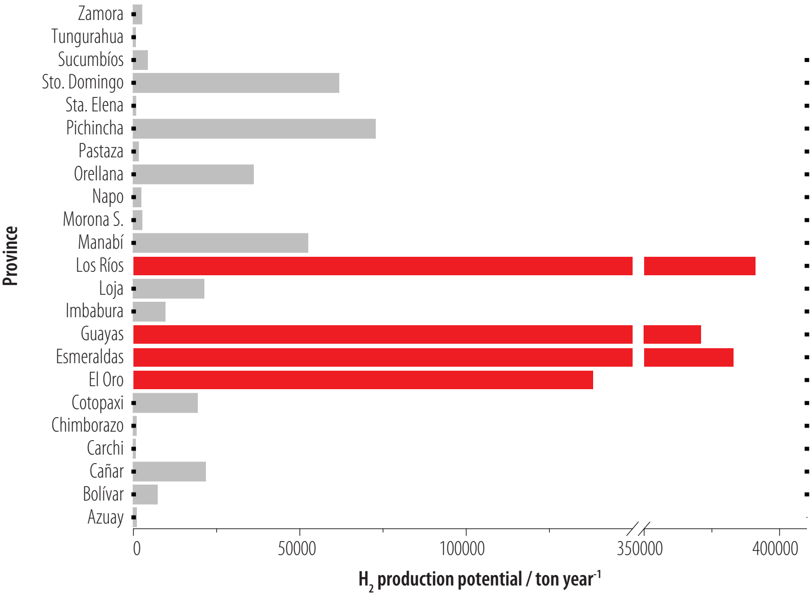

Figure 7. Hydrogen production potential from Ecuadorian biomass residues produced per location. Data from [15].

Porous materials

Porous materials have always attracted the scientific and industrial interest due to their ability to interact with atoms, ions, and molecules. Their performance on a particular application (e.g. ion exchange, adsorption (separation), catalysis) depends, to a great extent, on porosity, pore size and pore size distribution, specific surface area, and pore morphology [82]. Thus, the complete characterization and test methods used are extremely important. This work has found some scientific reports concerning the use of residual and yeast biomass as adsorbents for waste water remediation, and scaffolds for potential biomedical applications.

Wastewater remediation

Bioadsorbents from different biological sources have been investigated for removing heavy metals (see Table 3), such as lead, copper, chromium, which commonly end up in rivers, lakes and seas from industrial wastes. Campaña-Pérez *et al.* [83], reported the adsorption efficiency of three native yeasts for Cr(IV) from simulated wastewater. *Kazachstania yasuniensis, Kodamaea transpacifica*, and *Saturnispora quitensis* were isolated from soil samples collected in the Yasuní National Park, ephemeral flower samples from Isabela Island (Galápagos Islands), and fruit of an unidentified species of bramble from Maquipucuna forest reserve in Pichincha, respectively. The use of

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a cationic surfactant (solution of benzalconium chloride) for yeast conditioning duplicated the biosorption capacity above 80% for Cr(IV) concentrations up to 100 mg L^{-1}. For instance, the most efficient yeasts *Kodamaea transpacifica,* and *Saturnispora quitensis* showed biosorption capacities of about 416 and 476 mg Cr(IV) per gram of yeast, and specific surface areas, as high as, 1474.30 and 1588.27 m^2 L^{-1}, respectively. These values have shown the potential of the two isolates as low cost bioremediation agents. Andean Sacha inchi (*Plukenetia volubilis*) shell biomass (SISB), without any special treatment, has also been reported as a biosorbent for the removal of lead and copper from aqueous solutions. SISB showed adsorption capacities around 17 and 10 mg g^{-1} for Pb^{+2} and Cu^{+2}, respectively. Competitive values compared to other low cost bioadsorbents reported in literature [84]. Electrostatic attraction was stated as the mechanism of adsorption between the negatively SIBS surface, and the positively charged contaminants, being optimal at pHs between 3.0 and 6.0. Gallardo-Rodríguez *et al.* [85] studied bacterial biomass (Pseudomonas strains form aquaculture plants in the Ecuadorian Andes) inoculated on a biofilter packed with *Furcraea andina* fibers for removing Pb^{2+} ions. Samples with the bacteria supported on *Furcraea andina* fibers showed the maximum adsorption capacity of 48.75 mg g^{-1} at pH of 7. Interestingly, equilibrium batch biosorption assays revealed chemisorption as the Pb^{+2} removal mechanism.

Table 3. Summary of adsorption characteristics of different biomasses for wastewater remediation.

Biomass	Special treatment	Removed contaminant	Removal mechanism	Specific surface area (m2 L-1)	Max. Adsorption capacity (mg mg-1)	Ref.
Kazachstania yasuniensis	Pretreated with a cationic surfactant (solution of benzalkonium chloride)	Cr(IV)	Biosorption	1192.67	114.94	[83]
Kodamaea transpacifica				1588.27	476.19	
Saturnispora quitensis				1474.3	416.67	
Sacha inchi shell	-	Pb^{+2}		-	17.06	[84]
	-	Cu^{+2}		-	9.69	
Furcraea andida fibers	Bacteria biofilm	Pb^{+2}		-	48.75	[85]
Sadwust from pine trees	-	Heavy metals	Biosorption, flocculation, coagulation	-	-	[86]
Sugarcane bagasse	-			-	-	
Coconut coir	-			-	Al^{+3}:41 Pb^{+2}: 0.73 Cu^{+2}:1.35 Cr^{+2}: 0.22	

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Biomass	Special treatment	Removed contaminant	Removal mechanism	Specific surface area (m2 L-1)	Max. Adsorption capacity (mg mg-1)	Ref.
Sugarcane bagasse particles	-	Pb^{+2}	Biosorption	-	0.094	[87]
	-	Cd^{+2}		-	0.11	
Starch from plantain peels	Please refer to the reference	Heavy metals and particles	Flocculation	-	-	[88]
Pectin from orange peels				-	-	
Tamarind seed				-	-	
Palm shell	-	Organic compounds	Adsorption		5.63	[89]
Sawdust					32.78	

Moreover, sugarcane bagasse, sawdust from pine trees, and coconut particles (< 1mm particle size) without chemical modification were also applied for bioadsorption of heavy metals in wastewaters. According to Banchon *et al.* [86], heavy metals were removed up to 97.8% due to coagulation-flocculation processes were boosted by bioadsorption and ionic strength, reducing the consumption of chemicals (e.g. aluminum and polyacrylamide) up to 70%. In a later study, sugarcane bagasse particles packed in fixed bed columns have been also studied for the biosorption of lead and cadmium [87]. According to the authors, the adsorbents showed greater adsorption capacity for Pb^{+2} than Cd^{2+}, probably due to its higher electronegativity and smaller hydrated ionic radii. Nonetheless, this capacity was affected when the two contaminants were present in the aqueous media, showing a possible competition between the two ions for active sites at the adsorber. Natural organic polymers extracted from residues, such as starch from plantain peels (*Musa paradisiaca* L), pectin from orange peels, and tamarind seed extract showed, together with aluminum sulfate, equal or better characteristics as flocculants compared to commercial polymer PAM. Removal values of turbidity and color were around 87% and 92%, respectively, while pH adjustment was not necessary. However, the materials did not present any coagulant activity, and in economic terms, they seem not to be viable [88]. Concerning other contaminants present in produced water from oil and gas industries, Gallo-Cordova *et al.* [89] studied the adsorption of organic compounds from different residual biomasses (e.g. palm shell, orange, peel, banana peel, passion fruit peel, cocoa bean and sawdust). The adsorption experiments showed that only palm shell and sawdust were able to remove organic compounds from the aqueous media, with adsorption capacities about 5.6 and 32.8 mg g^{-1} of dry adsorbent.

Biomaterials for biomedical applications

Pupiales et al. [90] have pioneered the evaluation of using biomass waste for the production of porous scaffold via alkaline treatments. Scaffolds were synthetized by alkaline attack (NaOH) and varying reaction parameters, such as biomass concentration, temperature, NaOH concentration, operating time, and mesocarp dimensions (cacao variety CCN-51).

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Based on these results, a model was implemented to partially predict the behavior of the output reaction variables (e.g. lignin, cellulose, ash content and yield). Accordingly, NaOH concentration and temperature seemed to be the most important variables for generating porous structures rich in cellulose from cocoa pod shells. This study opened up, a new line of investigation concerning the application of bioporous materials in biomedical applications, e.g. in vitro cytocompatibility, and proliferation and differentiation.

CONCLUSION AND FUTURE DIRECTIONS

This contribution has shortly reviewed not only the most recent studies concerning the conventional chemical, biological and thermochemical conversion processes, but also the latest improvements for making value-added products from Ecuadorian residual biomass.

There is no doubt about Ecuador's potential to produce and utilize energy from biomass residues. Several studies have shown that conventional transformation methods (e.g. AD, fermentation, and pyrolysis) are better understood at lab-scale, and could be the milestone for scaling up into pilot and big scale plants. Interestingly, recently research articles have also revealed a further valorization of Ecuadorian biomass, aiming at the production of value-added goods, such as hydrogen, and porous materials (adsobers, scaffolds) that open-up new perspectives for a more efficient and environmentally centered bio-economy. However, there are still several economic and technological challenges to over-come in Ecuador not only related to basic research, but also implementation of renewable-friendly public policies. Therefore, it is crucial the application of the triple helix of innovation, which involves government, university, and industry for the production and dissemination of knowledge in pro of a bio-economy development.

AUTHORS CONTRIBUTION

Sebastián Ponce developed the literature review and prepared the initial draft, José Alvarez Barreto and Daniela Almeida Streitwieser contributed with fruitful discussions, revisions, and preparation of final manuscript.

CONFLICTO DE INTERÉS

Los autores declaran que esta investigación fue conducida en la ausencia de relaciones comerciales o financieras que pudieran constituir un potencial conflicto de interés.

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