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Potential for Farmers' Cooperatives to Convert Coffee Husks into Biochar and Promote the Bioeconomy in the North Ecuadorian Amazon

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Featured Application: Agricultural wastes generated in farmers' cooperatives constitute valuable resources for the bioeconomy and can be recycled into biochar to contribute to the implementation of economically and environmentally sustainable agricultural production in the forests of the Ecuadorian Amazon.

Abstract: Improving the livelihoods of communities living in fragile ecosystems, such as tropical forests, is among the main strategies to promote their conservation and preserve wildlife. In the Ecuadorian Amazon, farmers' cooperatives are recognized as an important mechanism to improve the socioeconomic conditions of local communities. This study analyzes the integration of pyrolysis processes to convert agricultural waste into biochar as a way to implement the bioeconomy in these organizations. We found that post-harvesting processes in the studied farmers' cooperatives are similar, and coffee husks are a potential feedstock to produce biochar. Although the environmental policies in Ecuador consider the valorization of agricultural waste, we did not find any specific standard to regulate the operation of pyrolysis facilities. Nonetheless, conversion of agricultural waste into biochar can contribute to (i) replacement of subsidized fossil fuels used in drying processes, (ii) prevention of environmental pollution caused by accumulation of waste, (iii) emergence of new income sources linked with the provision of carbon sequestration services, and (iv) the long-term maintenance of soil fertility. Currently, demonstration projects are needed to stimulate collaboration among farmers' cooperatives, academia, the government, international cooperation agencies, and existing forest conservation initiatives.

Keywords: agricultural waste; biochar; pyrolysis kilns; farmers' cooperatives; Amazon forests; coffee husks; soil; carbon sequestration

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1. Introduction

The Amazon rainforest covers six million square kilometers in north–central South America and is the largest tropical forest on Earth. It harbors the greatest terrestrial biodiversity and provides valuable global ecosystem services, including carbon sequestration, stabilization of biogeochemical cycles, and storage of freshwater [1]. In Ecuador, the Amazon region represents 45% of the territory and includes six national protected areas that are the home to diverse wildlife and the uncontacted Tagaeri/Taromenane group of Waorani indigenous people, who remain in voluntary isolation [2]. From the 1960s, petroleum extraction in the northern part of the Ecuadorian Amazon (NEA) and the Law of Agrarian Reform and Colonization (decree 1480) issued by the military government of 1964 have promoted the immigration of Ecuadorian citizens from other parts of the country to the NEA [3]. Job opportunities in agriculture and oil companies have also attracted Colombians, some seeking refuge from armed conflicts in their country [4]. In 1990, this immigration gave rise to the creation of new provinces with a population that has tripled since then, leading to the conversion of many forests into cropland [5].

The forest conservation literature argues that this sort of land-use change in similar tropical regions is intimately related to the poor socioeconomic conditions of the local communities that live in them [6–8]. Affording local communities the right to manage and restore forests may be a promising option to align global agendas for conservation, climate mitigation, and sustainable development [9,10]. In the NEA, the expanding African oil palm monocultures and large-scale cattle grazing are recognized as drivers of land-use change [11]. However, the poor socioeconomic indices in the region also undermine the conservation of the Amazon forest. In the NEA, 41% of the population live in extreme poverty, while the national average is around 12% [12]. Limited access to jobs for poor smallholders off their farms in the NEA has also been pointed out as a factor in the low levels of socioeconomic development. [13]. Nonetheless, the average size of a farm in the NEA, which is between 20 and 50 ha, is within the optimal size for a household to generate income in the regional context [2]. Within the framework of the People's Solidarity Economy Law [14], the Ecuadorian government and international cooperation agencies have been strengthening local farmers' cooperatives, and they are promoting the creation of new community organizations as a way to improve farm productivity and socioeconomic conditions of farmers in the NEA, thus preventing deforestation and land-use changes.

The contribution of farmers' cooperatives to the improvement of socioeconomic conditions of rural populations through the creation of local jobs is widely recognized [15]. Therefore, farmers' cooperatives and other types of community organizations are linked with a counter-cyclic effect during periods of economic crises [16]. Furthermore, farmers' cooperatives contribute to price stabilization by establishing fair commercial relations with large private companies [17]. In the NEA, the main interventions of the government and international cooperation agencies in support of the associative and cooperative sector have involved access to seed capital for the implementation of communal post-harvesting facilities, access to credit, training in management, training in agroforestry techniques, and access to international markets [18]. Currently, around 600 production and service cooperatives and organizations are registered in the Sucumbíos province of the NEA [19]. Nonetheless, despite significant growth of the associative and cooperative sectors, the socioeconomic conditions of local communities have not changed substantially, and the conservation of the Amazon forest remains a problem of major concern [20].

Recently, the United Nations Food and Agriculture Organization (FAO) has promoted the bioeconomy and the circular economy as ways to mitigate poverty in the rural sector of middle-income countries. The FAO defines the bioeconomy as the production, use, and conservation of biological resources, including knowledge, science, technology, and innovation related to them, to provide information, products, processes, and services in all economic sectors, with the purpose of moving toward a sustainable economy [21]. The FAO argues that the bioeconomy and the circular economy can promote the growth of farmers' cooperatives while improving their economic, environmental, and social performance. Thus, the sustainable growth of farmers' cooperatives through the implementation of the bioeconomy or circular economy can contribute to the conservation of tropical forests in the NEA. For rural agro-industry, bio- and circular economies converge on the importance of using agricultural waste as the feedstock for new productive processes [22]. In the NEA, agricultural waste is not valued by smallholders or their organizations, due to the lack of knowledge and logistical constraints, instead becoming a source of contamination. Therefore, the agricultural waste generated during the post-harvesting processes in farmers' cooperatives of the NEA have not been considered a resource for the local bioeconomy, much less as a resource with potential to improve the socioeconomic conditions of local communities within a strategy of tropical forest conservation.

Of the many technologies that are available for creating value from agricultural waste, pyrolysis stands out because it can be tailored for the conversion of waste into diverse carbon-related products. In general, pyrolysis is the thermochemical decomposition of biomass under oxygen-limiting conditions with the objective of producing solid carbonaceous materials, bio-oils, or synthetic gases. Recently, applications of the solid carbonaceous material that results from pyrolysis, often referred to as biochar, have attained extensive attention [23]. Biochar has important uses in agriculture, construction, climate change mitigation, environmental remediation, filtration of pharmaceuticals and other contaminants from water, energy production, cosmetics, and animal feed [24]. To the best of our knowledge, the conversion of agricultural waste into biochar has not yet been studied in the NEA in the context of implementing the bioeconomy and the circular economy in farmers' cooperatives. It is also still unknown the full extent that pyrolysis and biochar production may optimally play within farmers' cooperatives to promote economically and environmentally sustainable production systems in the NEA. Furthermore, it is uncertain to what degree the conversion of agricultural waste into biochar can help to meet the aspirations of rural development with low greenhouse gas emissions and reduce the pressures on the Amazon forests (i.e., deforestation).

The study of pyrolysis processes of different waste materials focuses on the influence of the of feedstock physicochemical properties, type of reactor, and operating conditions (i.e., temperature, pressure, and residence time) on the yield and physicochemical properties of the pyrolysis products [24,25]. Complementary studies focus on the properties and the potential applications of the pyrolysis products, such as the biochar [26,27]. Nonetheless, the practical implementation of pyrolysis technology in the context of the rural sector of middle-income countries, such as Ecuador and other Amazonian countries, has not been properly addressed. Considering that pyrolysis processes may contribute to the implementation of the bioeconomy, support the sustainable growth of local communities, and contribute to forest conservation, this study aims to explore the capacity of farmers' cooperatives in the NEA to implement pyrolysis processes to convert agricultural waste into biochar.

Accordingly, we describe the post-harvesting processes linked with the generation of agricultural waste and their current uses in four farmers' cooperatives located in the NEA. Furthermore, we examine technologies for the carbonization of waste that can be implemented by the farmers' cooperatives of the NEA. Carbonization technologies were examined following a set of criteria that were defined considering internationally recognized guidelines for the sustainable production of biochar. To identify potential constraints for technology adoption, we also analyze existing policies regarding the management of agricultural waste and the environmental standards that regulate the use of devices for energy conversion of waste within agro-industrial facilities in Ecuador. In the context of the bioeconomy and the circular use of resources, we examine the properties of biochar that can be of importance for the management of major environmental resources within and beyond the farms, namely, soil and water. Considering that biochar can also be used in new production processes, we discuss the biochar applications that can be of interest for the main sectors in the NEA, namely, the energy, animal husbandry, infrastructure, and the emerging carbon sequestration sectors. Complementarily, a SWOT analysis (strengths, weaknesses, opportunities, and threats) was performed to identify the current constraints and prospects for the implementation of pyrolysis facilities for the conversion of agricultural waste into biochar in farmers' cooperatives of the NEA. This study, in addition to providing a comprehensive baseline to foster the practical implementation of pyrolysis processes beyond the laboratory, can also be relevant to other countries where similar crops, forests, and processes are involved.

2. Methodology

2.1. Study Region

In Ecuador, the combined cultivation of coffee and cocoa in the NEA has been identified as a sustainable farming activity that allows smallholders to balance the price volatility associated with these commodities. In the NEA, 60% of farms include both of these crops, while 32% have only cocoa and 3% have only coffee [5]. Accordingly, this study draws on participative observations performed in four farmers' cooperatives located in the NEA that process cocoa and coffee. The four farmers cooperatives that are part of this study are shown in Figure 1, namely, the Asociación de Productores de Café Ecológico Lago Agrio APROCEL (0°09′21.1′′ N 76°50′47.8′′ W), the Federación de Organizaciones Campesinas de Shushufindi FOCASH (0°10′53.1′′ S 76°40′05.4′′ W), the Asociación Artesanal de Productores de Café de Dureno y Pacayacu, AGRODUP (0°03′31.2″ N 76°41′54.8′′ W), and the Asociación de Productores de Café y Cacao del Eno APROCCE (0°01′48.5′′ S 76°53′08.9′′ W). These four farmers' cooperatives belong to an informal local network of cooperatives that is currently supported by the European Committee for Training and Agriculture (CEFA). CEFA identifies these cooperatives as formal economic entities with a high degree of organizational maturity. The maturity of these cooperatives as selection criteria was determined by their age (between 15 and 17 years) and their formal registration in the Superintendence of the People's Solidarity Economy and the national tax service. CEFA introduced us to the leaders of these cooperatives. Thus, the post-harvesting operations and the potential heterogeneity in post-harvesting practices, along with differences in the management of agricultural waste between cooperatives, were characterized through field visits and open interviews with the president of each organization and the operational staff of each collection and processing center. The data gathered in the field visits (field notes and photograph registers) were later analyzed by the authors in the capital city of Quito through group meetings.

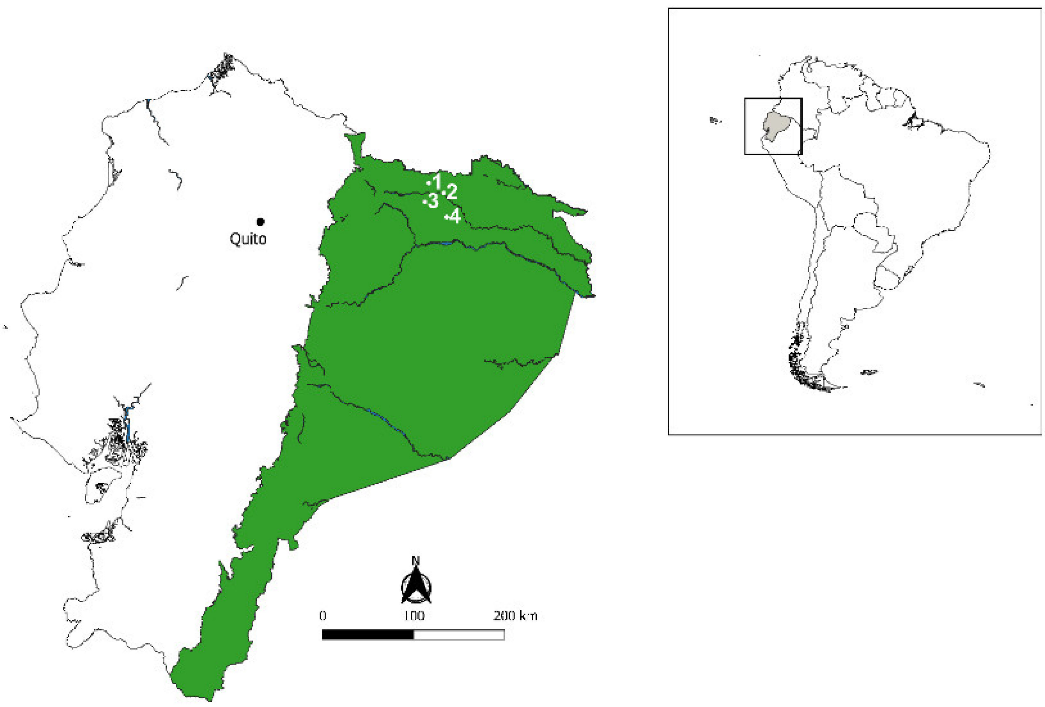

Figure 1. Location in the northern part of the Ecuadorian Amazon of the four farmer cooperatives studied: (1) APROCEL; (2) FOCASH; (3) AGRODUP; (4) APROCCE.

2.2. Criteria and Outline Conditions to Analyze the Adaptability of Pyrolysis Technology within the Farmers' Cooperatives

There is no policy framework in place for Ecuador to regulate the production and use of biochar. Therefore, the potential integration of pyrolysis technology within post-harvesting facilities located in NEA was discussed using the European guidelines for the sustainable production of biochar as a reference [28]. Table 1 summarizes the outline conditions and the exclusion criteria used to assess the technological alternatives disclosed in research articles and technical reports (i.e., pyrolysis reactors, furnaces, retorts, and kilns used to produce biochar). The databases consulted to explore the availability and characteristics of the different types of pyrolysis technologies were ScienceDirect, Scopus, ISI Web of Science, and ResearchGate. Pyrolysis systems that use agricultural waste as feedstock to produce bio-oil (fast pyrolysis) or syngas as a chemical feedstock for downstream processes (e.g., hydrogen or methanol production) have not been considered in the context of biochar production in the studied farmers' cooperatives.

Table 1. Criteria used to select pyrolysis technologies with the potential to be integrated within the farmers' cooperatives of the northern part of the Ecuadorian Amazon (NEA; see Section 2.1) following the European guidelines for the sustainable production of biochar [28].

	Criteria	Objectives
1	The pyrolysis facility makes effective use of pyrolytic gases to produce thermal energy.	Avoid the direct release of harmful pyrolysis gases and particulate matter emissions to the environment.
2	The carbonization temperature is continuously recorded and does not fluctuate more than 20%.	Guarantee homogeneity, reproducibility, quality, and traceability of the produced biochar.
3	The combustion of the pyrolysis gas supports an energy-autonomous carbonization process and fulfills the local/international flue gas composition regulations.	Prevent the use of subsidized fossil fuels to supply the heat required for carbonization and avoid the release of incomplete combustion products within the flue gas stream of the pyrolysis facility.
4	The external energy used for preheating and to operate the reactor (e.g., electricity, fossil fuels) does not exceed 8% of the agricultural waste's calorific value.	Minimize the use of subsidized fossil fuels in the post-harvesting facilities. Lower heating value of the coffee husks: 17.8 MJ/kg [29].
5	The excess heat produced during the carbonization process is recycled or integrated.	Use the waste heat from the pyrolysis process to provide the thermal energy consumed during the post-harvesting processes, which can promote the replacement of subsidized fossil fuels currently used in, e.g., drying processes.
6	The physicochemical properties of the produced biochar do not fluctuate more than 15%. Carbon content > 50 wt.%$_{db}$. H/C$_{org}$ molar ratio < 0.7. O/C$_{org}$ molar ratio < 0.4.	Guarantee homogeneity, reproducibility, and quality of the produced biochar.

2.3. Policy Analysis: Existing Laws Governing the Energy Conversion of Agricultural Waste in Farmers' Cooperatives of Ecuador

To perform the policy analysis, searches were made of the Official Registry, which is the dissemination organ of the Ecuadorian Government that publishes legal regulations [30]. The Official Registry publishes laws, decrees, regulations, and other acts and legal. The keywords used in the online search engine of the Official Registry were "residue" and "solid waste" (in Spanish). Two main supporting laws regarding waste management in Ecuador were identified, namely, the Organic Code of the Environment [31] and the Unified Text of Secondary Environmental Legislation (TULSMA, Texto Unificado de Legislación Secundaria de Medio Ambiente) [32].

As mentioned in Section 2.2, the pyrolysis facilities must use the pyrolysis gases to produce the thermal energy that is required by the carbonization process (Table 1). Accordingly, the conversion of pyrolysis gases into thermal energy requires a combustion process. To identify the policies that apply to combustion processes, the keywords "combustion", "biomass", and "boilers" were used in the online search engine of the Official Registry (in Spanish). It was identified that the valid policy that applies to combustion facilities that use biomass as feedstock in Ecuador is the Standard for Gaseous Emissions to the Atmosphere from Stationary Sources of Combustion [33]. It is worth noting that the integration of the excess of thermal energy produced during the carbonization process can help to replace the fossil fuels used in agro-industrial processes, for example, drying (Table 1). In Ecuador, the fossil fuels that farmers' cooperatives currently use in the post-harvesting processes are heavily subsidized by the government. Using as keywords "subsidies" and "fossil fuels" in the online search engine of the Official Registry, it was found that the regulation of the subsidies and the prices of fossil fuels in Ecuador are covered by the presidential decrees 1054 and 1158 [34]. All the regulations and decrees identified in this section were analyzed by the authors (literature review) focusing on the sections that regard agricultural waste (identified as solid waste and residues), the combustion of biomass in energy production processes, and the regulation of fossil-fuel prices.

2.4. Biochar Applications of Relevance for the NEA: Criteria for Classification

The body of literature regarding biochar uses and applications is abundant but scattered. Thus, in the Amazon region and the rural sector of middle-income countries, the link among biochar, the circular use of resources, and the implementation of a bioeconomy is not yet understood. In this study, the characterization of the processes that generate agricultural waste, the analysis of the technology required to convert them into biochar, and the analysis of the existing policies that can influence its implementation are major contributions toward the transfer of pyrolysis technology from the laboratory to the field. Nonetheless, it is important to provide the local communities and other institutions operating in the region (e.g., the government, NGOs, and agro-industries) with an organized outlook on the diversity of biochar applications. Accordingly, we defined six categories that are of major importance for the bioeconomy and social, economic, and environmental equilibrium in the NEA. The first categories have to do with two major environmental resources in the region—the soil and water—about which there is abundant scientific evidence of the effects of applying biochar. We also considered four other rising sectors in the region: the animal husbandry, energy, (green and gray) infrastructure, and carbon sequestration sectors.

According to the national management plans for the NEA, animal husbandry is a growing sector and one of the major drivers of land-use change [20]. Regarding the energy sector, the increasing urbanization rates in the NEA have produced an increase in energy consumption [5]. Hence, the identification of sustainable sources of energy to meet the increasing demand of Amazonian cities is of concern. Along with the increase in energy consumption, this increasing urbanization requires the expansion of public and private infrastructure. Thus, the biochar applications regarding green and gray infrastructures can be of relevance to promote the sustainable growth of the Amazon cities. Green infrastructure is a strategically planned network of natural and seminatural areas with other environmental features designed and managed to deliver a wide range of ecosystem services such as water purification, air quality, space for recreation, and climate mitigation and adaptation. Moreover, gray infrastructure refers to the human-engineered infrastructure using concrete and steel designed to avoid any type of ecosystem growing on it. Lastly, we consider that the application of biochar in agriculture is a way to reverse atmospheric carbon emissions by sequestering it into soils [35]. Accordingly, the monetization of carbon sequestration services may soon become an important source of income for farmers' cooperatives and smallholders in the region through international cap and trade deals. All data regarding applications of biochar in these selected categories were exclusively gathered via searches of ScienceDirect, Scopus, ISI Web of Science, and ResearchGate.

2.5. The SWOT Analysis

SWOT analysis is a tool for the analysis of complex situations and for the planning and definition of strategic actions that may have long-term consequences [36]. It aims at the identification of the internal and external constraints that can be associated with the implementation of pyrolysis technology to create value for agricultural waste within the studied farmers' cooperatives. The SWOT analysis explores the internal capabilities of the farmers' cooperatives that may facilitate this implementation and describes the potential opportunities that could result from adopting technology to convert agricultural waste into biochar. The SWOT analysis draws on the participant observations made in the field by the authors. CEFA introduced our team to the president of each farmer organization and the operational staff of each collection and processing center (Section 2.1). The aspirations and impressions of the leaders of farmers' cooperatives were gathered through open interviews and registered in field notes. In addition, the SWOT analysis was supplemented by the criteria of experts in thermochemical conversion processes, agroindustry specialists, and practitioners from international cooperation agencies with experience in the cooperative sector of the NEA. The analysis of the threats and weaknesses associated with the implementation of pyrolysis technology within the post-harvesting facilities of the NEA was also supported by a systematic review of the adaptability of pyrolysis technology (Section 2.2), the analysis of existing regulations (Section 2.3), and relevant case studies referenced in the scientific literature in which technologies for the conversion of agricultural waste have been integrated into an agro-industrial context.

3. Results and Discussion

3.1. Agricultural Waste Generated in the Post-Harvest Facilities of the NEA: The Status Quo.

In the field visits to the selected post-harvesting facilities (Section 2.1), it was observed that, in their collection and processing centers, they receive red coffee fruits ("coffee cherries") and cocoa seeds mainly from their associated farmers. According to the staff of the farmer´s cooperatives, the associated farmers transport these products in small trucks from their farms to be processed in these communal centers (Figure 2a). In the case of cocoa, farmers collect the pods and extract the seeds in their farms manually and then deliver them to these communal centers to be fermented and dried. Accordingly, all the agricultural waste generated during the harvesting of cocoa (i.e., empty pods, pruned branches) remains on the farms.

Unlike cocoa, the entire red coffee fruits are harvested and delivered to these centers, where they are processed according to the dry method, in which the moisture of these fruits must be reduced to about 10% by weight before threshing. The threshing (or hulling) machines, which are driven by electric or diesel motors, separate the coffee grain from the rest of the fruit (Figure 2b). The extracted husks include the outer skin, the pulp, and the parchment, with particle sizes in the range of 4 to 10 mm. The staff of the post-harvest facilities estimate that that 1 kg of husks are generated per kg of coffee beans produced. The coffee husks are the predominant agricultural waste observed in the four studied facilities (Figure 2c).

Inside the collection and processing centers of FOCASH and PRIMAVERA, there are small, sheltered storage rooms in which the coffee husks generated during the threshing process are stored. When the amount of coffee husks generated is high, concrete structures (Figure 2d) are sometimes used to store the coffee husks, as in the case of APROCEL. Coffee husks, unlike other agricultural wastes, such as palm kernel cake or corn stems, are not used as feed for livestock, due to their low digestible protein content and low palatability [37]. In interviews with the presidents and workers of the farmers' cooperatives, it was mentioned that agricultural waste is currently stored until it can be transported back to the farms to be re-incorporated into the soil whenever trucks are available. The staff of the centers said that the incorporation of coffee husks into the soils is a way to prevent their accumulation in the centers. However, they indicated that no appreciable benefits are observed for the crops, such as increases in yield or reduced fertilizer input. Although coffee husks contain potassium and other minerals, their incorporation into the soils without adequate treatment (e.g., composting or vermicomposting) has negligible effects on the crop yields [38]. Therefore, the limited benefits that result from the incorporation of coffee husks in the soils and the high cost of transporting them back to the farms often dissuade this practice and lead to their accumulation in these processing centers, where storage capacity is often exceeded.

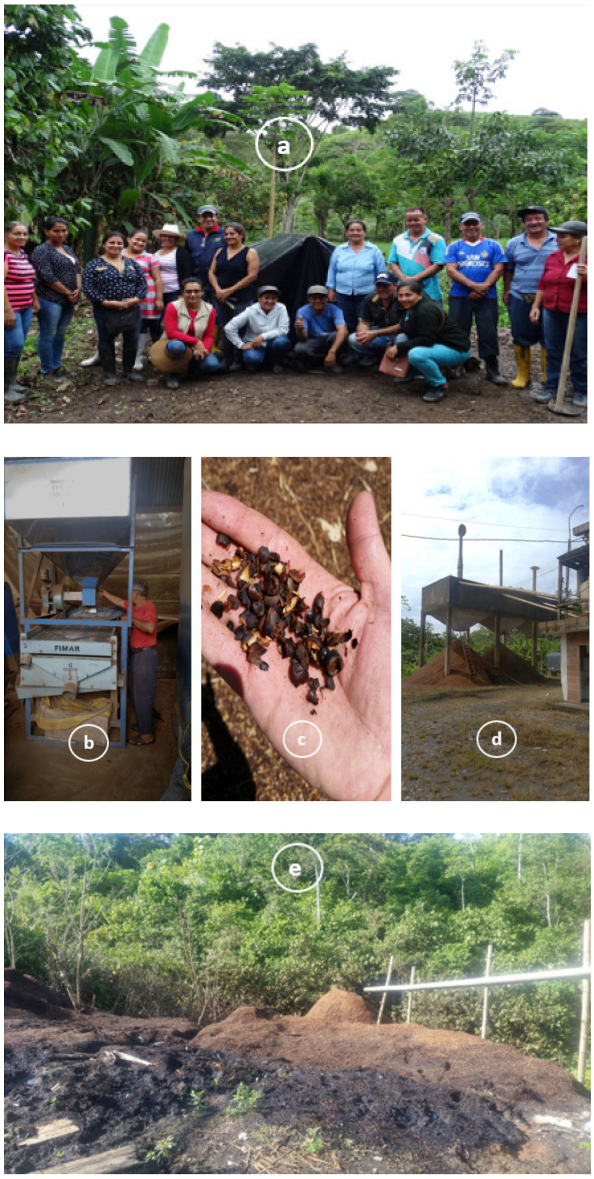

Figure 2. (**a**) Farmers in a cocoa and coffee plantation in the Ecuadorian Amazon; (**b**) an operator of one center during the process of threshing dry coffee fruits; (**c**) coffee husks that were separated during the threshing process; (**d**) one of the studied centers used a concrete hopper to store their coffee husks; (**e**) the coffee husks from one of the studied centers were dumped directly into a nearby creek.

In AGRODUP, the accumulation of coffee husks is a major environmental concern, since they are dumped into a nearby stream (Figure 2e), when the storage capacity is exceeded, threatening aquatic ecosystems downstream. Frequent rain in humid tropical areas causes the leaching of caffeine, free phenols, and tannins (polyphenols) from coffee husks, leading to groundwater pollution and soil acidification [39]. The high temperatures and moisture in such areas promote the decomposition of accumulated coffee husks, which is linked with the release of methane, a greenhouse gas whose global warming potential is 84–87 times that of CO_2 when considering its impact over a 20 year timeframe and 28–36 times that of CO_2 when considering its impact over a 100 year timeframe [40]. The decomposition of 1 kg of agricultural waste can release roughly 0.19 kg of methane [41]. Moreover, it was observed that the decomposition of agricultural waste, such as coffee husks, attracts mosquitoes. Mosquitoes are disease vectors that can threaten the people who live near these processing centers [42].

The drying of red coffee fruits and cocoa beans is one of the main activities at these processing centers. During times of less rain, this is done by spreading them on drying yards or in greenhouse dryers, with the process being driven by solar energy and natural convection. Each of these four centers also has a fixed-bed mechanical dryer with forced convection and thermal energy input from the combustion of diesel, liquefied petroleum gas (LPG), or wood (Figure 3). According to the staff, these mechanical dryers are used on rainy days because the cloud cover and the high humidity, typical of the NEA, hinder the drying process in solar dryers. Delayed drying can lead to the formation of mold, which reduces the quality and market price of these products.

Figure 3. (**a**) Industrial dryer with two fixed beds at two levels (light blue) and threshing machine (yellow) in APROCEL; (**b**) a diesel burner, a heat exchanger, and an air blower provide thermal energy for a fixed bed dryer.

According to workers of these centers, the use of logs or coffee husks as fuel to produce thermal energy for the mechanical dryers results in a significant amount of smoke, and the temperature inside the drying room is less than optimal. They point out that the drying temperatures can vary between 30 °C and 50 °C, depending on the initial moisture of the material and the stage of drying. Combustion of agricultural waste, such as coffee husks, with no pretreatment, such as drying or particle size homogenization (pelletization), releases harmful compounds, including dioxins, furans, and carbon monoxide [43], which are often associated with improper or incomplete combustion. The combustion of untreated coffee husks has also been linked to the buildup of slag on the combustion grate, corrosion, and fouling of the heat exchange devices [44]. Thus, these cooperatives prefer to use diesel and LPG, which they have access to under subsidized prices thanks to authorization from the Hydrocarbon Regulation and Control Agency (ARCH, Agencia de Regulación y Control Hidrocarburífero) up to a limit of 1000 gallons per month (4546 L). Despite the subsidy, the presidents of these cooperatives stated that the fuel costs of mechanical dryers are too high.

3.2. Policies and Standards Linked with the Energetic Use of Agricultural Waste in Ecuador

In Ecuador, prices for gasoline, diesel, and LPG have been subsidized since the 1970s up to 85% of international prices [45]. Thus, during the last 50 years, agro-industries have benefitted from steady and low energy prices. Recently, Presidential Decree 1054 of May 2020 reformed the regulation of fossil fuel prices [34]. The current trading scheme is linked to international oil prices, and the price of fossil fuels is updated monthly by the national oil company, Petroecuador. The price is adjusted according to a system of fluctuating bands of ±5%. Likewise, Presidential Decree 1158 of September 2020 allowed the importation of fossil fuels by the private sector, an activity that was previously reserved for Petroecuador.

Following these decrees, the price of fossil fuels, such as diesel, has increased 5% monthly on average concerning the average price of the last 10 years. Although these cooperatives indicated that the cost of mechanical drying was already too high, this will apparently continue to increase in the near future.

The proper use of the agricultural waste generated during the threshing operations through pyrolysis can be an alternative to provide the thermal energy required by these cooperatives and replace diesel and LPG with a renewable energy source. According to current environmental regulation (TULSMA), coffee husks are within the definition of nonhazardous solid wastes [32]: "any object, material, substance or solid element that does not have dangerous characteristics, and that results from the consumption or use of a good in domestic, industrial, commercial, institutional, or service activities" or "residues having no value for the person/institution that generates it, but that is susceptible to use and transformation into a new good with added economic value".

Regarding the transformation of agricultural waste into a new good, the Organic Code of the Environment [31] states that local municipalities are responsible for providing the service of solid waste final disposal, while the Environmental and Water Ministry has the duty of control and supervision. Currently, the only alternative provided by the municipalities for solid waste final disposal is placement in landfills. It is important to note that, at the national level, barely 20% of the local municipalities have sanitary landfills that are managed within the proper standards, while the remaining 80% use uncontrolled open dumps [46]. To address the alarming environmental impacts linked with open dumps, the Environmental and Water Ministry has promoted, since 2010, the National Program for the Integral Management of Solid Waste (PNGIDS, Programa Nacional de Gestión Integral de Desechos Sólidos) [47,48]. The PNGIDS considers the implementation of waste-to-energy processes and recycling processes, opening the door to converting waste into materials for new production processes. PNGIS states that waste-to-energy processes and recycling processes are alternatives to decrease the load on landfills, but the practical focus of the program has been to provide financial and technical assistance to local municipalities to replace the open dumps with proper landfills.

TULSMA and the Organic Code of the Environment also consider mechanical, thermal, and biological processes as alternatives for the treatment of solid wastes or energy recovery. However, there are no specific details, nor is there a proper description for each of these technological alternatives. Furthermore, it is not clear if coffee husks generated during the threshing processes can be given value through pyrolysis in situ at the farmers' cooperatives or if they should be collected by environmental managers authorized by the municipalities and the Environmental and Water Ministry. Therefore, only these environmental managers could make use of these mechanical, thermal, and biological processes for the energetic conversion or recycling of the agricultural waste. One example is that large-scale agro-industries in Ecuador (e.g., the sugar cane or the palm oil sectors) already make use of their agricultural waste as a feedstock in thermal power plants within their facilities, to produce heat and electricity (i.e., cogeneration). With this precedent, the farmers' cooperatives could transform agricultural waste within their facilities, for example, by pyrolysis processes. Nonetheless, no clear statements about this were found in the regulations.

The major policies and standards that regulate the energetic conversion of agricultural waste in Ecuador are linked to the production of electricity in large-scale facilities. In Ecuador, the second-largest renewable energy producer in terms of installed capacity is the sugar cane sector, which currently has 144.3 MW_e of installed power [49], and existing environmental regulations are dedicated to controlling this activity. Considering the "environmental technical standards for the prevention and control of environmental pollution for the infrastructure sectors: electric, telecommunications, and transportation (ports and airports)", the energetic conversion of agricultural waste into process heat and electricity by combustion processes is regulated only in facilities with a thermal power higher than 3 MW_{th}. These facilities are subjected to environmental audits every 6 months [50]. Although the energetic conversion of agricultural waste in facilities up to

3 MW_{th} is not subjected to environmental control, existing policies and standards state that their electricity production capacity should be registered in the Electricity Regulation and Control Agency (ARCONEL) to obtain an operating license. For those facilities that, rather than electricity, aim to produce other forms of energy, such as carbon-based products (e.g., biochar), which is the case of pyrolysis processes, the need for registration in ARCONEL should be considered at least ambiguous.

According to the criteria for selection (Table 1), the pyrolysis gases generated during the carbonization process should be burned to prevent the direct release of harmful compounds to the environment in the form of flue gas and to provide the thermal energy required by the carbonization process supporting an energy-self-sufficient process. In this regard, the "Standard for Emissions to the Air from Stationary Combustion Sources" issued by the Environmental and Water Ministry [33] establishes emission limits of particulate matter, nitrogenous compounds (e.g., NO_x, NO_2), carbon monoxide, and sulfur dioxide within the flue gases. However, this refers to the biomass boilers in the sugar cane sector. In contrast to this type of cogeneration system, the fuel that is burned in pyrolysis facilities is in the gaseous phase (i.e., the pyrolysis gas). Therefore, it is unclear if the current emission standards [33] can be considered as a reference for facilities that burn gaseous fuels generated during the carbonization of agricultural waste. Furthermore, this regulation also regards cogeneration facilities with an installed thermal power higher than 3 MW_{th}. According to the members of the farmer´s cooperatives (Section 2.1), the quantity of agricultural waste generated per year in their processing centers does not exceed 1000 tons (as received basis). Therefore, the power of an energy conversion facility integrated within these processing centers would not surpass the threshold of 3 MW_{th}. This estimation considers that the thermal power that can be recovered from a pyrolysis facility with a load capacity of 1200 t/year is 150 kW_{th} [51].

From the policies and regulations that were analyzed (Table 2), although the conversion of agricultural waste into value-added products is considered in the main Ecuadorian environmental regulation (the TULSMA and the Organic Code of the Environment), there are no specific laws or standards to control or supervise thermochemical conversion processes, such as pyrolysis, or other types of recycling technologies. The existing environmental regulations regard the energetic conversion of agricultural waste in cogeneration plants with a thermal power superior to what could be implemented in farmers' cooperatives. In addition to the pyrolysis processes significantly differing from that combustion processes, the thermal energy required by these farmers' cooperatives is also below this threshold. Therefore, the implementation of the pyrolysis technology as an alternative to promote the bioeconomy in the farmers' cooperatives and the rural sector will require the development of specific regulations for the medium- and small-scale sectors (under 3 MW_{th}) to define and normalize the thermochemical conversion processes that take place in a pyrolysis facility, along with regulations regarding the pyrolysis products (e.g., biochar). Nonetheless, whether the innovative technology should arise before the legislation is still a topic of discussion.

Table 2. Policies and standards linked with the energetic use of agricultural waste in Ecuador.

	Policies and Standards	Reference
1	The Unified Text of Secondary Environmental Legislation (TULSMA, Texto Unificado de Legislación Secundaria de Medio Ambiente)	[32]
2	Standard for Gaseous Emissions to the Atmosphere from Stationary Sources of Combustion	[33]
3	Presidential Decrees 1054 and 1158	[34]
4	The National Program for the Integral Management of Solid Waste (PNGIDS, Programa Nacional de Gestión Integral de Desechos Sólidos)	[47]
5	Environmental technical standards for the prevention and control of environmental pollution for the infrastructure sectors: electric, telecommunications, and transportation (ports and airports)	[50]
6	The Organic Code of the Environment	[31]

3.3. Technological Alternatives for the Conversion of Agricultural Waste into Biochar in the Studied Farmers' Cooperatives

In tropical regions, the production of charcoal is often performed in masonry kilns, mud kilns, retorts, and converters [52]. The use of masonry and mud kilns constitutes a major environmental and health concern because harmful compounds within the pyrolytic gases are released with no treatment into the environment [53]. Although the carbonization temperature can be recorded and the physicochemical properties of the charcoal may be homogeneous when using masonry and mud kilns, avoidance of the release of pyrolysis gases into the atmosphere is one of the selection criteria (Table 1). Unlike mud kilns, the retorts and converters can be adapted to recover energy and other products from the pyrolysis gases (e.g., liquid condensates, tars, and syngas) while avoiding the direct release of pyrolysis gases into the atmosphere [54]. Nonetheless, retorts and converters are tailored for the use of forest biomass as feedstock (e.g., logs, large pieces of wood). The use of agricultural waste (Figure 2c) to produce charcoal in retorts and converters is less well known and may require studies and major adaptations. In particular, models of retorts and converters are not adapted to the use of agricultural waste with particle size several times smaller than forest biomass, in addition to the significant differences in physicochemical properties.

For the rural sector of low- and middle-income countries, flame-curtain kilns and modern biomass cooking stoves (e.g., top-lit updraft stoves, TLUDs) have emerged as alternatives for biochar production [55]. Flame-curtain kilns are low-complexity alternatives to produce biochar that are mostly adapted to the use of forest residues as feedstock. Flame-curtain kilns are inverted pyramid shaped kilns or deep-cone bowls that could be made of steel and as a simple soil pit, consisting of a conically shaped hole in the ground. Unlike retorts and converters, flame-curtain kilns reduce the waste of residual biomass during the initial heating process [56]. However, it is difficult to recover the heat generated during the carbonization process in flame-curtain kilns for use in drying and other processes (Figure 4). Several models of TLUDs, in contrast, are well adapted to efficiently use various types of agricultural waste [57]. However, the yield of biochar is usually too low to supply more than a single farm or to sell it as charcoal (0.5 to 1 kg per batch). Probably, the case of bigger community TLUDs [58] that produce up to 10 kg of biochar per batch would be more convenient, given the quantity and type of agricultural waste produced in these farmers' cooperatives and our selection criteria (Table 1). Nevertheless, the typical batch operation of TLUDs will result in an intermittent supply of thermal energy, and the drying operations in these processing centers would need to be adapted accordingly.

The simplicity of flame-curtain kilns and TLUDs facilitates local construction and implementation of pyrolysis facilities in rural areas. However, they allow for little or no monitoring and control (e.g., for temperature) during the carbonization process. Accordingly, the properties and quality of the resulting biochar can be uncertain and highly variable, breaching Criteria 2 and 6 (Table 1). Although the physicochemical characteristics of biochar produced in TLUDs and flame-curtain kilns can be in accordance with international standards for safe application in soils [59], some studies of biochar that was produced at low temperatures in simple carbonization kilns have also found high concentrations of polycyclic aromatic hydrocarbons and heavy metals, which can threaten soil health [60,61].

As an alternative, auger-type reactors and rotary kilns are industrial models that can guarantee energy self-sufficiency (Figure 4), traceability, quality, homogeneity, and replicability of the physicochemical properties of the produced biochar in agreement with the selection criteria (Table 1) [62,63]. Auger-type reactors and rotary kilns allow for continuous operation and facilitate the productive use of the heat that is generated during the carbonization process [64]. A tentative design of the pyrolysis process integrated into the farmers' cooperatives allows part of the heat that is generated during the carbonization of coffee husks to be used to replace diesel and LPG in the mechanical drying process (Figure 4). Following the selection criteria (Table 1), the burning of pyrolysis gas should lead to energy self-sufficiency. The required monitoring to guarantee the biochar quality and homogeneity is also facilitated.

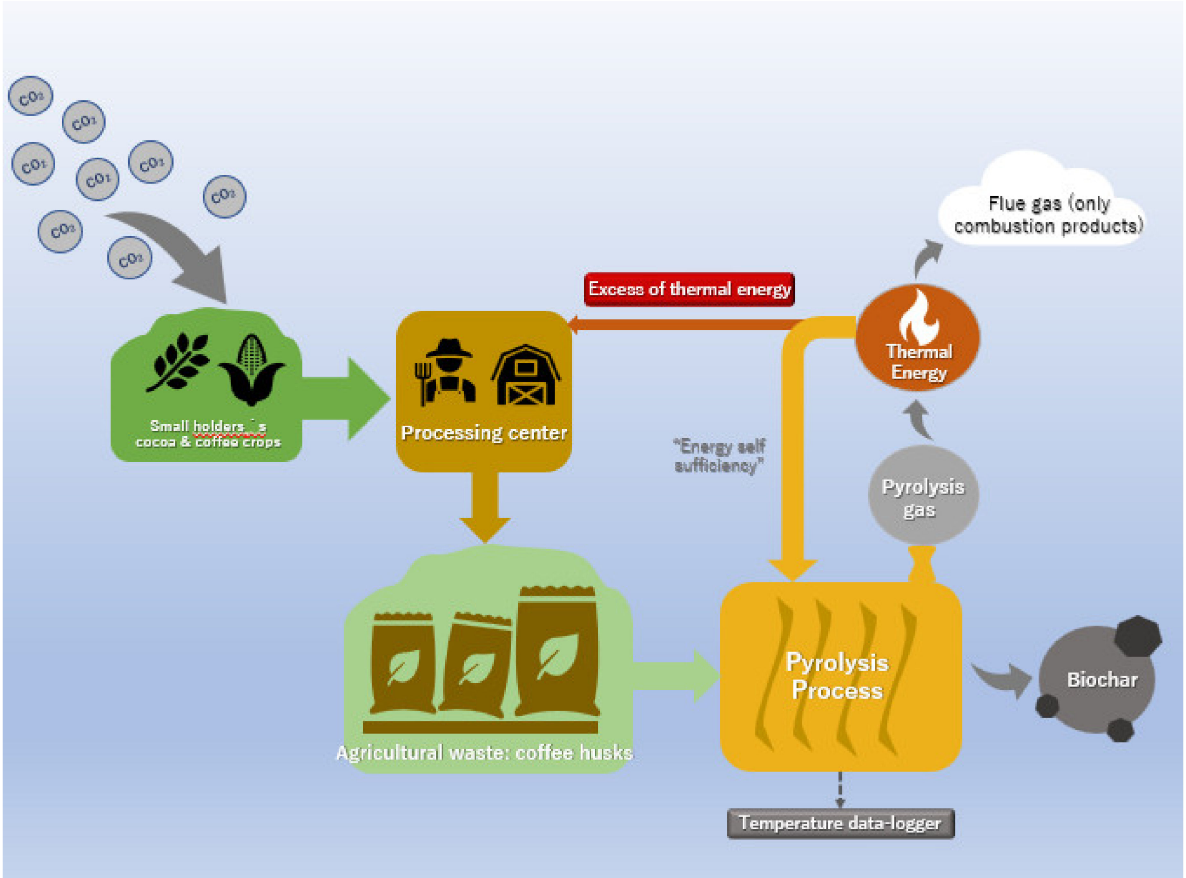

Figure 4. Tentative design of a pyrolysis process integrated into local processing centers. The heat generated by the combustion of pyrolysis gases is used to drive the carbonization process and to replace the fossil fuels that are currently used in mechanical drying. This complies with the selection criteria (Table 1).

The combustion of pyrolysis gases is of major importance to meet Criteria 1 and 3–6 (Table 1). One concern, however, is that the combustion of gases with high tar content as the pyrolysis gases has been linked with increased particulate matter (PM) emissions, namely, PM_{10}, $PM_{2.1}$, and nitrous oxide emissions [65]. The control of these pollutants requires the implementation of complex processes of combustion and flue gas treatment, such as flameless oxidation (FLOX) processes, electrostatic precipitators, bag filters, or cyclones [66]. Therefore, the production of high-quality biochar in auger and rotary kiln reactors results in elevated initial investment costs (>500,000 USD) and high maintenance costs. These high costs would increase biochar prices to the range of 600–900 USD/t, which is out of reach for farmers in low- and middle-income countries [67].

Patents and the payment of licenses linked with the use of complex pyrolysis equipment are mechanisms that give preferential access to state-of-the-art technology to countries in the Global North to the detriment of low- and middle-income countries in the Global South [68]. In this regard, open-source technology can play a key role in democratizing knowledge on carbonization processes and facilitating access in low- and middle-income countries to efficient, safe, and affordable designs of pyrolysis facilities. On an increasing scale of complexity, the Kontiki Kiln (a type of flame-curtain kiln [69]), the Cornell University Pyrolysis Retort [70], and the Pulpa-pyro Reactor [71] are open-source designs that can be fabricated locally and adapted for use in rural areas of middle-income countries. The Cornell University Pyrolysis Retort [70] and the Pulpa-pyro Reactor [71] satisfy the selection criteria (Table 1). Nonetheless, these open-source technologies can require significant engineering input to adapt the original designs that are optimized for the use of forest biomass as feedstock to the use of agricultural waste. Major modifications must be expected to be implemented considering the significant differences in the physicochemical properties of residual forest biomass and agricultural waste. Unlike wood chips or wood pellets, the low density of agricultural waste (e.g., coffee husks) may present the following problems: irregular feeding to the reactor, bridging in the storage facilities and hoppers, blockage of feeding valves or transporting systems, and unwanted secondary reactions in the feed line [72]. In this context, the consolidation of knowledge of carbonizations processes and skills in the handling and processing of agricultural waste among local practitioners and engineers can be a crucial factor for the successful and efficient integration of open-source designs of pyrolysis equipment in the rural sector of low- and middle-income countries.

A pilot-scale pyrolysis experiment in Ecuador with a continuous reactor demonstrated the integrated use of pyrolysis gases as an energy source for the carbonization process [73]. This modular system integrates an auger-type reactor and has a starting biomass burner that uses agricultural waste as feedstock to initiate the carbonization process. Thereafter, the pyrolysis gas generated is burned to produce thermal energy and support the pyrolysis process, in agreement with the selection criteria (Table 1). This modular system has proven to be effective for the production of biochar from agricultural waste with both high density (i.e., palm oil kernel shell) and low density (i.e., coffee husk, quinoa husk, and quinoa stems) [29]. A complementary pilot-scale experience in Ecuador demonstrated the carbonization of residual biomass generated during the extraction of *Jatropha curcas* (Barbados nut) oil using an electrically heated auger-type reactor [74]. In this case, the use of high-quality energy vector (i.e., electricity) to produce a low-quality energy vectors (i.e., heat to drive the carbonization processes) is detrimental to the energetic efficiency of the process. Furthermore, the high voltage required to supply the facility can restrict the implementation of this type of reactor in isolated rural communities with limitations in the supply of electricity and does not comply with Criteria 1, 3, and 4 (Table 1). Of all of the pyrolysis technologies that were analyzed, only auger-type reactors, rotary kilns, the Cornell University Pyrolysis Retort, and the Pulpa-pyro Reactor comply with all six of the selection criteria (Tables 1 and 3).

Table 3. Compliance of different pyrolysis technologies with the selection criteria (Table 1).

Pyrolysis Technology	**Selection Criteria**					
	1	**2**	**3**	**4**	**5**	**6**
Masonry kilns and mud kilns	✘	✘	✘	✘	✘	✔
Retorts and converters [a]	✔	✔	✔	✘	✔	✔
Flame curtain kilns [a]	✘	✘	✘	✔	✘	✘ [d]
Top-lit updraft stoves (TLUDs) [b]	✔	✘	✔	✔	✔	✘ [d]
Auger-type reactors and rotary kilns [c]	✔	✔	✔ [e]	✔	✔	✔
Open source: Cornell University Retort and Pulpa-pyro Reactor [f]	✔	✔	✔ [e]	✔	✔	✔

[a] Batch operation using wooden logs. These devices are not adapted to the use of agricultural waste with low-density feedstocks. [b] Intermittent supply of thermal energy due to batch operation and low yield of biochar. [c] Industrial models with high initial investment costs and high maintenance costs. [d] Implementation of continuous monitoring (Criteria 2) can contribute to produce biochar with homogeneous and safe properties with these devices. [e] Complex combustion technologies and flue gas treatment processes are required to meet flue gas emissions regulations. [f] Open-source reactors can require significant engineering input to adapt the original designs to operation with agricultural waste.

3.4. Potential Applications of Biochar in the NEA

The physicochemical properties and yield of biochar can change according to the type of feedstock, the type of reactor, and the operating conditions (e.g., temperature, residence time, or pressure) [75]. Accordingly, the biochar can be used for a variety of purposes, some of which involve high technology, such as fuel cell systems, catalysts for the cleaning of syngas, and biodiesel production or fabrication of supercapacitors [76]. Other, lower-tech applications require fewer post-treatments, for instance, production of inks, soil amendment, or useful energy production. According to the criteria discussed in Section 2.4, biochar has a wide variety of productive and profitable applications in the NEA (Table 4).

Table 4. Applications of biochar in the NEA considering five categories: soil, water animal husbandry, energy, green and gray infrastructure, and carbon sequestration.

Category	Benefits of the Use of Biochar ([1])	References
Soil	- Increases water-holding capacity, cation exchange capacity, and organic matter content. Reduces irrigation water consumption. - Alters soil pH, especially if the soil is overly acidic. - Provides a suitable medium for the reproduction and maintenance of soil microorganisms. - Reduces bioavailability and ecotoxicological impacts of heavy metals (Cu, Ni, Cd, Pb). - Retains natural and added soil nutrients (N, P, K, Si, Ca) against leaching, such that they can be absorbed again by plants. Increases crop yields. - Improves the organic waste composting process.	[23,26,27,76–80]
Water	- Adsorptive removal of chemicals including pharmaceuticals and antibiotics, inks (e.g., methylene blue), and other inorganic pollutants from water. - Prevents the eutrophication of aquatic environments when applied on land, by keeping the nutrients there. It can be also used in filtering bags in the river runoff.	[42,76,81–85]
Animal husbandry	- Supplements feed for ruminants (cattle and goats), pigs, poultry (chicken and duck), and fish. - Improves ruminal fermentation and feed efficiency. - Positively affects growth performance, blood profiles, egg yield, abdominal fat weight, meat quality, carcass weight, and nutrient excretion. - Can also be used as bedding material in stables.	[86–89]
Energy	- Source of thermal energy in the production of iron or steel. - Fuel in boilers and cogeneration facilities. - Cooking fuel, barbecue charcoal. - Increases methane yield when used as an additive in anaerobic digestion systems.	[53,54,90–92]
Green infrastructure	- When used as a substrate in rooftop and vertical gardens, decreases the weight and corresponding load of these infrastructures. - Preserves the ecosystems services linked to urban greenery (when used as a soil conditioner). - Improves the water retention of rain gardens and helps to control stormwater runoff. - When used as a soil conditioner in urban greenery, as well as vertical and rooftop gardens, reduces infiltration and inflow of rainwater controlling sanitary sewer overflow.	[93–95]
Gray infrastructure: cement and mortars	- The addition of small fractions of biochar (<5 wt.%) increases the strength and toughness of the cement and mortar, as well as the flexural strength. - Decreases density of cement mortar, making it more porous and lightweight). - Reduces thermal conductivity. - Reduces carbon footprint of infrastructures made with cement. - Turns gray infrastructure into long-term carbon sinks.	[96–98]
Carbon sequestration	- Biochar is recalcitrant in the soils turning them into a long-term carbon sink with several co-benefits for crops (see soil above). - Transfers carbon from the atmosphere into the soils.	[41,99–102]

[1] This column presents the results of studies with biochar produced from different feedstocks and operating conditions. Differences in the context and characteristics of these studies should be considered before extrapolation of results. Any field application must be previously studied experimentally.

For the bioeconomy, the creation of value for agricultural waste is important if it results in the emergence of new production processes. In this regard, biochar is a versatile material that can be appropriate for the sustainable management of environmental resources in the NEA and as an input material in major sectors of the region. Concerning the soil as an environmental resource, the use of biochar for amendment purposes can contribute to the sustainability of farming systems [23]. In the context of the circular economy, the use of biochar to amend soils is also a contribution toward the recycling of soil nutrients [103,104]. For instance, a published study that was made using samples collected in the analyzed processing centers as feedstock to produce biochar showed that the content of inorganics in ash after the pyrolysis process increases from 7.1 wt.% in the raw feedstock to 15 wt.% in the resulting coffee husk biochar [29]. The major components within the inorganic content of the biochar made from coffee husks are elements of relevance to soil fertility, namely, potassium (52 wt.%), phosphorous (5 wt.%), calcium (13 wt.%), and silicon (15 wt.%) [105]. These elements are taken from the soil during the growth of the coffee trees and, if not returned to the soil, have to be added by the farmers via synthetic or organic fertilizers. Nonetheless, the effective incorporation of minerals embedded in the biochar matrix into the soil depends on biogeochemical cycles. Thus, it may take decades until these nutrients are available to the plant roots [106].

Considering the importance of the minerals and carbon embedded in the biochar for the soil, the use of coffee husk biochar in a sector other than that of agriculture (e.g., infrastructure, energy) can cause the loss of these nutrients. In the case of the energy sector, recycling the ashes after the combustion of biochar back to the soil should be organized to avoid the loss of minerals in the soil. This implies that biochar should not optimally be transported out of the region/country for its energy conversion. Furthermore, there should be a protocol for the return of ashes back to the farms. With respect to the energy sector, the process proposed here produces thermal energy during the carbonization of agricultural waste (Criteria 5, Table 1), and its recovery can replace the subsidized fossil fuels that are currently used by farmers' cooperatives for drying coffee fruits and cocoa grains (Figure 4). In this way, the use of this pyrolysis process by farmers' cooperatives can reduce their consumption of fossil fuels and their dependence on government subsidies (Section 3.2).

Biochar has also important properties for the environmental management of water. Application of biochar to soil increases its water-holding capacity, which would be very appropriate in abundant dry areas of Ecuador on the coast and in the Andes, to reduce the need for irrigation water and to mitigate the impact of droughts. However, this would require transport and would lead to the transfer of carbon and nutrients between regions. Biochar can also be used as filtering media in environmental remediation processes of contaminated drinking water or sewage [42,76,81,84]. Thus, the production of biochar in farmers' cooperatives can be a contribution to the efficient and sustainable use of water resources.

Green infrastructure represents an intersection of the use of biochar as a soil amendment, water resources, and urban development. The increasing urbanization rates in the NEA, together with the heavy local rains, require sustainable alternatives to control runoff water. Roof-top and vertical gardens are alternatives currently considered by urban planners as strategies to manage stormwater runoff in cities. Unlike rainwater gardens or ponds, roof-top and vertical gardens do not require valuable urban land. The use of biochar in roof-top and vertical gardens, in addition to the benefits for growing of plants (Table 4), increases the water-holding capacity of the substrate, thus retaining more stormwater with less structural weight loading. Likewise, the use of biochar expands the diversity of plants that can be planted in these gardens to include species with higher water demand [95]. In addition to reducing total stormwater volumes, these gardens amended with biochar also delay peak runoff and improve the quality of the stormwater [93].

Another significant potential application of biochar in the NEA is its use as a feed supplement in the animal husbandry sector (Table 4). The "cascade" application of biochar, in which biochar is added to animal feed supplement because it is beneficial to the animals and continues to be beneficial as a component of their manure and of the soils it is applied onto, would be very important for cattle ranching in the NEA. In such a system, biochar would be enriched with organic nutrients during its transit through the digestive tract of animals, in the bedding material of stables, in manure pits, or during co-composting. Thus, this biochar would become a more efficient plant growth-enhancing soil amendment that promotes the recycling of nutrients from organic residues of animal husbandry that otherwise would be lost [89].

In the context of a bioeconomy, carbon sequestration services provided by farmers through the application of biochar to their land may become a significant, new source of income. The application of biochar produced by the farmers' cooperatives in the associated farms can promote a model of smart and environmentally friendly agriculture in the NEA. As recognized by the IPCC, the direct use of biochar in agriculture provides an important route for carbon sequestration and storage in terrestrial ecosystems and, thus, climate change mitigation [35]. Carbon marketplaces are emerging as a way to turn biochar application in soils into carbon removal certificates with monetary value [107]. Then, these carbon removal certificates can be traded with companies, institutions, governments, and individuals interested in reducing their carbon footprint [108]. Complex traceability systems that apply blockchain technologies and/or satellite imaging are being implemented to promote trust, accountability, and reliable guarantees of the carbon deposited in a certain sink [109,110]. Certifications of the carbon sink potential or verified carbon standards such as the Verra as a 'gold standard' have been emerging [111–113]. However, the quantitative evaluation of the carbon sequestered on farms and the monitoring of potential changes in long-term land use are still major concerns for the large-scale deployment of carbon sequestration services. Intended double counting is also regarded as a concern because already traded carbon removal certificates could be added to national mitigation strategies. In this regard, the use of biochar as an additive in gray infrastructure (Table 4) can have advantages in terms of carbon sink accounting, compared to agriculture application. Unlike the soil, the amount of carbon deposited in a construction in the long term can be more accurately predicted [114,115]. Accordingly, the growth of infrastructure in the NEA due to the high urbanization rates can be a great opportunity to provide carbon sequestration services by including biochar in the cement and mortars of public and private structures.

3.5. SWOT Analysis: Challenges and Opportunities Associated with the Integration of Pyrolysis Facilities in Farmers' Cooperatives of the NEA

The conversion of agricultural waste into biochar in farmers' cooperatives can be a productive way to implement profitable new activities in line with a bioeconomy in several sectors of the NEA (Table 4, Section 3.4). Nonetheless, the financial sustainability of such pyrolysis operations remains a concern. Economic sustainability of a pyrolysis process that uses reactors that comply with the selection criteria (Table 1; e.g., rotary kilns, auger type reactors) requires biochar prices to be above 600 USD/t [116], while typical soil amendments used in the NEA (e.g., composted chicken manure) do not cost more than 25 USD/t. Therefore, it is unlikely that farmers' cooperatives would invest in the production and use of biochar in agriculture [117]. Nonetheless, Table 5 shows that the monetization of carbon sequestration services linked to the use of biochar in agriculture could become a new source of income and an opportunity to extend the business model of farmers' cooperatives that is currently based solely on commodity production to also include climate services. Furthermore, the implementation of pyrolysis facilities in the farmers' cooperatives of the NEA can generate new nonfarm job opportunities to the rural sector [118], which could significantly improve the socioeconomic conditions of local communities and, thus, contribute to the conservation of the Amazonian rainforest. According to Table 5 one potential limitation is the capacity of farmers' cooperatives in the rural sector to assemble people with technical skills to install, operate, and maintain the pyrolysis facilities. Getting started with this new technology is impeded by the fact that no international manufacturers of pyrolysis equipment have representatives in Ecuador or

Latin America. Thus, there is no technical support for the selection and adaptation of the technology or for its maintenance.

Table 5. Selected results of a SWOT analysis to explore constraints and prospects concerning implementation of pyrolysis facilities in farmers' cooperatives of the NEA.

	Strengths	Weaknesses
Internal	- Availability of dry feedstock with a homogeneous particle size stored in a single location. - Farmers' cooperatives are likely to receive support and non-reimbursable financial aid from NGOs and international forest conservation initiatives. - Sufficient physical space available within processing centers. - Ample distribution network for soil application of biochar on the farms of the members. - Members have experience in the use of organic soil amendments. - Associative values (solidarity, cooperation) are complementary to carbon sequestration services, the circular economy, and the bioeconomy. - Farmers' cooperatives already have contacts with international customers potentially interested in reducing their carbon footprint.	- Farmers' cooperatives have a life cycle that depends on qualitative dynamics between the members (e.g., trust, wellbeing perception). - Continuous changes in leadership hinder long-term planning of projects. - Difficulty in access to bank loans and services. - The associative model is rigid and restricts access to external investors or joint ventures. - Difficulty in assembling competent people to manage, operate, or provide maintenance of new technologies. Lack of experience with pyrolysis. - Lack of structured learning or research processes to innovate with pyrolysis technology or biochar applications. - Lack of experience in developing alternative sources of income or new business models beyond the sale of coffee and cocoa. - Farmers' cooperatives are influenced by the flaws/weaknesses in the People's Solidarity Economy Law. The level of government support is dependent on political ideology in power.
	Opportunities	**Threats**
External	- Emerging carbon marketplaces may help to monetize carbon sequestration services provided by farmers. - There are companies abroad with climate strategies, as well as interested in reducing their carbon footprint and promoting social impact. - There are low-cost, open-source designs for biochar production. - There is research and experience in pyrolysis technology and biochar uses in Ecuador. - Progressive removal of subsidies and rising prices of fossil fuels should spark interest in alternative energy sources, including agricultural waste. - There is still time to be the first innovators in this field in the region. - Synergies can be established in the intersection of carbon sequestration, forest conservation initiatives, the green and gray infrastructure sector, and the animal husbandry sector. - Pyrolysis kilns could carbonize other agricultural waste (e.g., corn cobs, palm oil kernels) to add value. - Potential implementation of new cooperative cycles, for instance, the creation of energy cooperatives to manage pyrolysis facilities. - Partnerships with the academic sector could result in novel carbon-based products and services. - Creation of new jobs and nonfarm sources of income in the agro-industry sector and rural areas.	- Unexpected policy restrictions in the future: at present, there are no specific regulations for biochar production or for its application in soils in Ecuador. - Currently, biochar is not a product within the domestic market of agriculture or animal feed supplements. - The need for high-cost certifications from external/private companies to monetize carbon sequestration services. - Unclear initial investment costs and unavailability of technical support. There are no sales representatives of international manufacturers of pyrolysis equipment in Ecuador. - Pyrolysis technologies adapted to the use of residual forest biomass may not be able to process tropical agricultural waste, such as coffee husks. - Use of biochar in domains other than the soil may break the carbon cycle and the ability to recycle soil nutrients. - Market dynamics, e.g., the higher price of barbecue charcoal compared to the price of biochar for use in agriculture may stimulate its use for energy purposes. - High international demand for biochar may stimulate its exportation, breaking the circular local economy model.

Although the provision of carbon sequestration services in Ecuador is not an entirely new topic, the monetization of the carbon sequestration service that results from the application of biochar in soils has not been considered as a source of income alternative for farmers' cooperatives. In Ecuador, carbon sequestration services date back to 1993 when a consortium financed by Dutch electricity companies promoted the absorption of their CO_2 emissions through the implementation of forest conservation and reforestation plans in the highland provinces of Pichincha, Cotopaxi, and Chimborazo [119]. In general, carbon sequestration through forestation and reforestation activities results in the fixation of 100 metric tons of CO_2 equivalent per hectare [119]. The use of biochar in agriculture, in contrast, could sequester up to 526 metric tons of CO_2 equivalent per hectare. This estimation is based on an agriculturally relevant application of biochar of 195 metric tons/ha [77], since 2.7 tons of CO_2 equivalent can be sequestered per ton of biochar [41,102]. It is worth to note that the amount of CO_2 sequestered will vary depending on the amount of biochar applied to the soil, the production technology used, the feedstock logistics (collection and transportation), and, of course, the soil dynamics influencing the effective incorporation of carbon to its structure. It is also identified that the emerging carbon certification standards and marketplaces that allow for the monetization of these services are private initiatives at the international level that probably are not within the reach of farmers' cooperatives. These carbon marketplaces demand life-cycle analysis of the produced biochar as the first step of certification, and such analyses are not familiar for farmers' cooperatives. Accordingly, governments could play a significant role in converting certification into a public service rather than a private good [18], thereby democratizing access to the carbon trading markets.

These farmers' cooperatives are formal economic institutions and already have contact with national and international customers. Some of these customers have climate strategies and may be interested in reducing their carbon footprint. The farmers' cooperatives can meet this demand for carbon sequestration services by providing an extended positive environmental impact by preventing pollution caused by the accumulation of agricultural waste, contributing to forest conservation, and replacing fossil fuels used for drying with renewable sources of energy. The provision of carbon sequestration services by farmers' cooperatives can also be linked with a complementary positive social impact via creation of new jobs and new sources of income in the rural sector (see opportunities in Table 5). Likewise, the strengthening of the policy that removes the subsidies on fossil fuels can also be a positive complementary effect at the local level. In this way, the implementation of carbon sequestration services in the farmers' cooperatives can consolidate a solid and quantitative contribution toward the conservation of Amazonian forests and argue for environmentally friendly chocolate and coffee in international certification programs.

It is important to note that the implementation of pyrolysis facilities in the farmers' cooperatives and the provision of carbon sequestration services will require significant financial resources in addition to those already required to remain competitive. Unlike traditional small and medium enterprises, the ownership structure of farmers' cooperatives limits access to capital. In most cases, the financial resources available in the cooperatives come from the profits generated in the sale of commodities (e.g., cocoa or coffee) and the provision of services (e.g., drying and threshing) to independent farmers. The members of the farmers' cooperatives benefit from the infrastructure and activities carried out by the association but cannot claim rights over its capital in the case of getting out of business. The presidents of each organization confirm that the most important decision-making body in the organizational structure is the assembly of partners, which must approve any interventions of external investors. Generally, the venture capital required to implement innovations involves a percentage of ownership by the investor to drive companies toward a quick return on the investment, but the organizational structure of cooperatives does not allow for this. Therefore, the ownership structure of these cooperatives is not normally attractive to typical sources of venture capital, such as external investors and even banks (see weaknesses in Table 5).

Internal funding sources may be available (e.g., retained earnings), along with non-reimbursable grants from NGOs, the government, or international programs for the conservation of the Amazonian rainforest. However, these funding sources may not be enough to satisfy the financial requirements needed to establish pyrolysis technologies and develop business models for carbon sequestration services [120]. In this regard, alternative sources of financing are emerging at international level for the cooperative sector, together with debt instruments that may bring access to additional capital. Special types of shares are an example in which the cooperative member shares are based on usage of the cooperative infrastructure. Other emergent mechanisms that allow cooperative members to trade their shares according to the appreciation of the value of the cooperative are also emerging [121]. Reserving all or most voting rights for cooperative members is also an alternative to raise external capital keeping the cooperative control with its members. In this regard, previous experiences show that cooperative members often conclude that their interests would be better served by conversion to the corporate model. In other cases, cooperatives were not financially successful after attracting outside investors, leaving the failed business in the hands of external creditors [122]. A further consideration is that, even when members retain legal control, outside investors may still exercise influence over the cooperative.

As show in Table 5, the internal governance of these cooperatives is another matter of concern. Their internal dynamics, such as assembling competent people, having effective team management, rotation of board members, and the use of problem-solving orientation methods will also have an influence on the implementation of new technologies and business models, such as those related to pyrolysis processes [123]. In general, farmers' cooperatives, like these, after an initial phase of development, reach the technical and economic consolidation phase [124]. In the consolidation phase, their ability to process and market their agricultural products is strengthened. Only after the consolidation phase can they start considering differentiating their economic and productive activities, making their processes more complex. During the consolidation phase, when the maturity of the association has not yet been achieved, disagreements often emerge among members, due to different preferences or discrepancies in the perception of wealth, which lead to frictions between subgroups that then turn into conflicting factions [125]. As the interests of the members diverge, the planning and the execution of long-term projects become more difficult. This is aggravated by their internal regulations that require the continuous rotation of board members and election of new leaders every 2 years. Therefore, the degree of maturity is critical for the implementation of new technologies, such as pyrolysis operations and associated activities.

A discussion on whether the conversion of agricultural waste into biochar can provide motivation for the emergence of new associations and cooperative cycles is worthwhile. As shown in the section opportunities of Table 5, the development of new cooperatives can be motivated by the implementation of pyrolysis facilities and their related services. Thus, smallholders of the NEA can form new cooperatives to manage and get profit from pyrolysis facilities. In this regard, decentralized, nongovernmental community and citizens' initiatives to promote the production and consumption of renewable energy in Europe can be a reference for the implementation of new concepts of farmers' cooperatives linked to the implementation of pyrolysis facilities in the NEA [126,127]. Relevant cases of cooperatives that aim to foster the production and consumption of renewable energy can be found prospering especially in Canada, the United States, the United Kingdom, Denmark, and Germany [128]. It should be highlighted that market dynamics may give preference to profitable applications of biochar, rather than those of environmental interests within a circular economy (see threats in Table 5). For instance, a higher price of barbecue charcoal in comparison with that paid by the monetization of carbon sequestration services may give preference to the energetic use of biochar.

Another concern regards the People's Solidarity Economy Law that regulates the operation of farmers' cooperatives in Ecuador (threats in Table 5). This law does not explicitly consider the provision of energy services or waste management services as an activity for the emergence of new cooperatives. Others regard it to be excessively rhetorical, with regulations that do not necessarily match up with the real needs of the rural sector [129]. Furthermore, its ambiguous and never-ending definition of what a people's solidarity company is [130] may be a potential weakness toward the emergence of energy cooperatives in the NEA and the rural sector of Ecuador.

The implementation of a bioeconomy in the rural sector of Ecuador must consider that start-ups and small and medium enterprises are the traditional pioneers and drivers of innovation. In turn, innovations emerge backed up by the research and development activities of the academic sector in an environment of preferential business policies, tax incentives, and abundance of risk capital [131]. According to the SWOT analysis of Table 5, development of the capacities of farmers' cooperatives to implement formal means of learning, along with research and development programs, should be included within the programs implemented by the government and NGOs. Furthermore, strong cooperation between the farmers' cooperatives of the NEA and the local academic sector would be critical for the adaptation and implementation of pyrolysis and other innovative processes. The literature also shows that the deployment of a single industrial technology becomes economically worthwhile when different industries/cooperatives at the same site come together to consolidate an industrial ecosystem in which the different companies supply each other with intermediate products and/or energy, thus making economies of scale possible by the proximity of the various players, in terms of the key competitiveness factors of logistics and investment [120].

The implementation of pyrolysis facilities in farmers' cooperatives of the NEA should consider interaction with other local actors that also generate agricultural waste (e.g., corn and palm oil sectors). Farmers' cooperatives can provide them with waste management services and carbon-based products, such as biochar. Likewise, the potential use of biochar in animal husbandry, in green and gray infrastructure, in water treatment, or for energy (Table 4) are other reasons to promote the exchange of services and the emergence of new economic activities. Promoting a resilient industrial complex that relies on diverse, complementary interactions and exchanges among the main sectors of the NEA is a major task. This ability to link sectors that traditionally are not used to cooperating/exchanging/trading may be as critical as the need for financial resources and technology toward the implementation of these pyrolysis operations [132].

4. Conclusions

The current global climate mitigation agendas are largely based on forest conservation and reforestation. For the forest conservation literature, the inclusion of local populations and the improvement of their livelihoods have been recognized as major mechanisms to prevent deforestation. Accordingly, the identification and implementation of technological means to improve the economic, environmental, and social conditions of communities currently living in or near the forests are of major importance. In the NEA, farmers' cooperatives are formal economic entities with years of experience bringing together, organizing, and empowering local communities. FAO considers the creation of value for the agricultural waste that is generated by these cooperatives to be an opportunity to establish a bioeconomy. In turn, the creation of value for agricultural waste can bring new productive activities and new job opportunities to improve the socioeconomic conditions of local communities in the NEA. We explored the potential of four farmers' cooperatives located in the NEA to implement pyrolysis processes to convert their agricultural waste into biochar. We found that the post-harvest processes are similar in the four cases analyzed. For these farmers' cooperatives, the agricultural waste (i.e., coffee husks) generated in their processing centers currently has little to no economic value and is not useful in agriculture. Ecuadorian policies do not restrict the creation of value for agricultural waste, but there are no specific regulations or standards regarding the implementation of thermochemical conversion processes such as pyrolysis. In Ecuador, the most relevant environmental policies are concerned with controlling the production of electricity in cogeneration plants of more than 3 MW_{th} that simply use agricultural waste as fuel. Therefore, there are no specific standards or regulations that can be used as a reference for the implementation of pyrolysis processes to convert agricultural waste into biochar. The lack of policies and standards to regulate pyrolysis processes can be interpreted as a measure of the innovative nature of this idea.

Although the literature on pyrolysis and biochar is vast, few studies have addressed its implementation in the field. In this study, biochar applications that could be very important to major sectors in the NEA are featured. Concerning the circular use of resources, the use of biochar for soil amendment and carbon sequestration is preferable, as it can return to the soil important minerals and mostly carbon. Furthermore, the heat generated during the carbonization of agricultural waste can be used to replace the fossil fuels currently used in the farmers' cooperatives for the mechanical drying processes. Nonetheless, the farmers do not have the economic resources to acquire pyrolysis facilities in which the produced biochar should be marketed at the international prices (600–900 USD/t). In this regard, the monetization of carbon sequestration services based on the application of biochar to soils could make this economically feasible for these farmers' cooperatives. For this, the development of carbon sink certifications and proper business models, both adapted to the context of farmers' cooperatives, would be required.

Pyrolysis technologies that can guarantee a sustainable production of biochar have high capital and maintenance costs, namely, rotary kilns and auger reactors. As expected, these investments are out of the reach of these cooperatives. Open-source designs of pyrolysis devices can be an alternative for implementation of pyrolysis technology for local communities, but the adaptation of these designs to this case will require major financial, engineering, and research efforts that are not within the reach of these cooperatives. Nonetheless, Ecuador has considerable research experience at the pilot scale that demonstrates the technical feasibility of using the coffee husks as feedstock for the simultaneous production of biochar and heat through pyrolysis, which could help advance this concept. In this regard, the development of formal cooperation among farmers, academia, governmental institutions, international cooperation agencies, and forest conservation programs is necessary to advance the implementation of demonstration facilities. The consolidation of demonstration projects with the participation of multiple stakeholders in the region would be key to stimulate the exchange of services and products between farmers' cooperatives and other important sectors of the regional economy, such as agro-industry (e.g., African oil palm plantations), cattle ranching, and energy production. The opportunities for establishing a bioeconomy in the NEA will be feasible as long as the pyrolysis technology promotes a complex and diverse exchange of products and services among private companies operating in the market, the public sector, farmers' cooperatives, and NGOs. These findings are also relevant for other types of cooperatives within the People's Solidarity Economy Law and private agro-industries (e.g., the palm oil sector) in the NEA and other Ecuadorian regions. This study can also be a reference for the implementation of pyrolysis facilities in local communities living in forests and agro-industries of other middle-income countries.

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