Sustainability analysis of rural biorefineries to strengthen the cocoa value chain in Colombia

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Agro-industrial value chains play a crucial role in the economies of many rural regions, providing employment and income to millions of producers. However, the initial stages of the chain, particularly harvesting and post-harvest processes, encounter multiple challenges that hinder the efficiency and sustainability of the production system [1]. A major issue is the biomass loss resulting from harvesting, storage, and transportation practices. These losses not only reduce producers profitability but also generate large volumes of organic waste, which, in most cases, are inadequately managed. Several rural regions, agricultural and agro-industrial residues are often perceived as valueless waste and are consequently disposed of through unsustainable methods, such as open burning or uncontrolled dumping. These practices result in significant environmental impacts, including greenhouse gas emissions, soil and water contamination, and the proliferation of pests and diseases. However, these residues hold considerable potential for valorization [2]. These residues are considered of raw materials for new production processes enhancing the sustainability of rural communities. The valorization of agro-industrial waste presents a viable opportunity for implementing the biorefinery concept in rural areas. A biorefinery is a system designed to convert biomass into multiple value-added products, including bioenergy, bioplastics, biofertilizers, and industrially relevant chemical compounds [3]. This approach not only helps mitigate environmental pollution but also diversifies producers income sources and promotes the development of circular economies. However, when analyzing biorefineries in rural areas, different approaches must be considered, such as the type of processes to be implemented, processing scale, type of product to be obtained, and ease of marketing. The process to be implemented in rural areas must involve technologies that do not require specialized labor. Therefore, physical processes such as extraction or thermochemical transformations with little control are the most suitable. The processing scale is key to defining the type of process that can be viable in a rural area. Finally, the type of product (i.e., food or agricultural products with high demand) that can be marketed in the same region is a key factor that limits the process proposed in rural biorefineries.

Cocoa is widely consumed worldwide. In 2024, cocoa production was estimated at 2.24 million metric tons, with a market share of USD 114.7 billion (Gavrilova, 2024). The World Cocoa Foundation (WCF) has reported a total of cocoa growers in the world 5 6 million, of which 70 to 80% correspond to small producers located in rural zones [5]. In Colombia, cocoa production is estimated at 73 thousand tons in 2024. However, the cocoa value chain in Colombia and around the world presents deficiencies in waste disposal and the economic benefits of the products. In this sense, the aim of this research was to assess the sustainability of various biorefinery schemes by considering the valorization of the waste generated during the harvest and post-harvest stages. The proposed biorefinery schemes were designed with a rural-oriented approach to strengthen the cocoa value chain in Colombia. The first stage involved experimental work, where cocoa samples were collected from one of Colombia most promising producing regions. A chemical characterization of residues (i.e., extractives, cellulose, hemicellulose, lignin, pectin, starch, protein and ash) was done including pod husks and leachates generated during fermentation [6]. Different valorization alternatives were evaluated at this stage, including the production of biopesticides, cocoa butter, bioactive compounds, pectin, animal feed, biogas, and biofertilizers. **Figure 1** shows the biorefinery schemes analyzed. The first biorefinery scenario involved biopesticide, cocoa butter, enriched polyphenolic compounds, pectin, and biochar production. The second biorefinery scenario was obtaining biopesticide, cocoa butter, enriched extracts of polyphenolic compounds, pectin, and animal feed. The third biorefinery scenario considered biopesticide, cocoa butter, enriched extracts of polyphenolic compounds, pectin, biogas, and biofertilizer production. Cocoa fermentation was carried out in rural areas, considering the relative humidity and temperature of the region. The fermentation was monitored for 5 days by measuring pH, temperature, °Brix. The leachate was obtained in the first two days of fermentation and was collected and stored at -4°C without light. The leachate was characterized by gas chromatography using the reported method by Brands et al. [7]. The cocoa butter was extracted using a hydraulic press. Cocoa pod husks were stored at -4°C, dried at 45°C, and ground to a particle size of 40 mm. Polyphenolic compounds were extracted with 30% v/v ethanol, 40°C, 200 rpm, solid: liquid ratio 1:10 for 3 hours [8]. The extracts were characterized by Total Phenolic Compounds, flavonoids, and antioxidant capacity using DPPH and ABST [9]. Pectin extraction was performed with citric acid, pH 3, and solid: liquid ratio of 1:25, 250 rpm, 95°C for 95 min [10]. Pectin was characterized to determine galacturonic acid content, degree of esterification, and methoxy content [11]. Biochar production was performed at 190°C for 30 min [12]. Biogas was produced using a volatile solids ratio of cocoa pod husk and inoculum of 0.4, 37°C for 20 days. The biogas was characterized using a Gasboard 3200P analyzer. The second stage involved process simulation using Aspen Plus V.14 software to obtain the material and energy balances of the biorefinery schemes. The operating conditions were defined based on the experimental tests performed. Finally, the third stage considers technical, economic, environmental, and social analysis. The technical analysis was performed by calculating mass and energy indicators such as Product yield, annual productivity, Process Mass Intensity, Overall energy efficiency, self-generation index, and specific energy consumption using the methodology reported by [13]. Economic analysis was performed to determine the economic feasibility of biorefinery scenarios using the methodology reported by [14]. The environmental impact of the scenarios was carried out considering a Life Cycle Assessment approach using the ISO 14040 methodology. A cradle-to-gate approach was considered, where the inventory of the agronomic stage was obtained from interviews with producers.

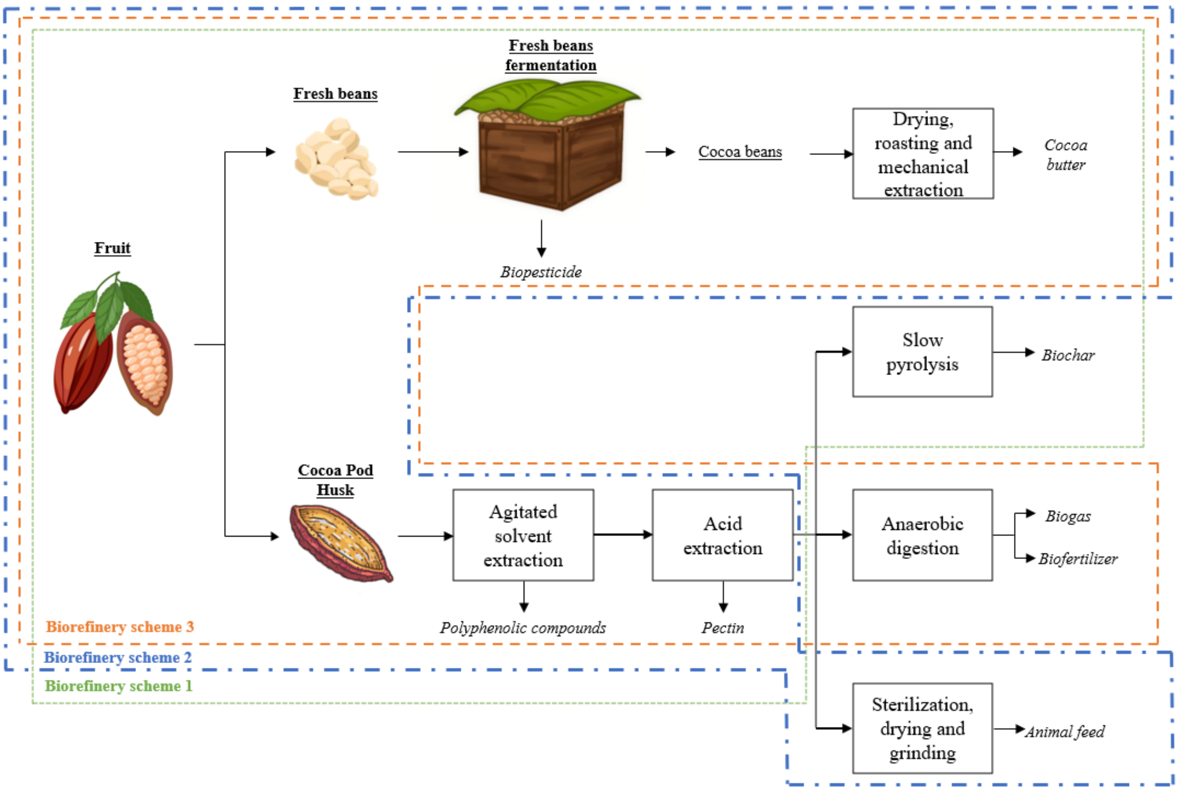

Figure 1. Proposed biorefinery schemes for strengthening the cocoa value chain in rural areas.

The chemical composition of cocoa pod husk was determined as follows: 28.37±2.84% extractives, 34.15±0.78% cellulose, 19.56±0.85% hemicellulose, 8.46±0.54% lignin, 15.94±1.98% starch, and 1.97±0.05% ash. During the first two days of fresh bean fermentation, 31 mL of leachate per kilogram of beans was generated, with acetic acid, ethanol, and butanol concentrations of 16.82%, 6.56%, and 4.25%, respectively. The extracted polyphenolic compounds exhibited a high flavonoid content, with significant amounts of theobromine and caffeic acid. The antioxidant capacity of these polyphenol-rich extracts suggests their potential application in the food, pharmaceutical, and agricultural industries, particularly as a fungicide. The pectin extraction yield was 11.63±2.27%. The characterization of galacturonic acid content, degree of esterification, and methoxy content confirmed pectin's suitability for use in the food industry as a gelling agent. Experimental results on biochar, biogas, and animal feed production were consistent with those reported in the open literature.

The techno-economic and environmental assessment of the proposed biorefinery scenarios was done to elucidate the best option to upgrade cocoa and cocoa residues. The scenario with biochar production applying the slow pyrolysis process was the best option to upgrade cocoa residue since the product yield was higher than the results obtained in the other scenarios (i.e., animal feed and biogas). Moreover, biochar is the best option from the economic and environmental perspectives since this solid material has a high selling price and high capacity to capture carbon dioxide. The second scenario was the animal feed product. The scenario with the lowest techno-economic and environmental performance was the biogas production since the revenues are lower compared to the other scenarios.

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