Life cycle sustainability assessment of plantain-based biorefineries in emerging industrial countries: Colombia case study.

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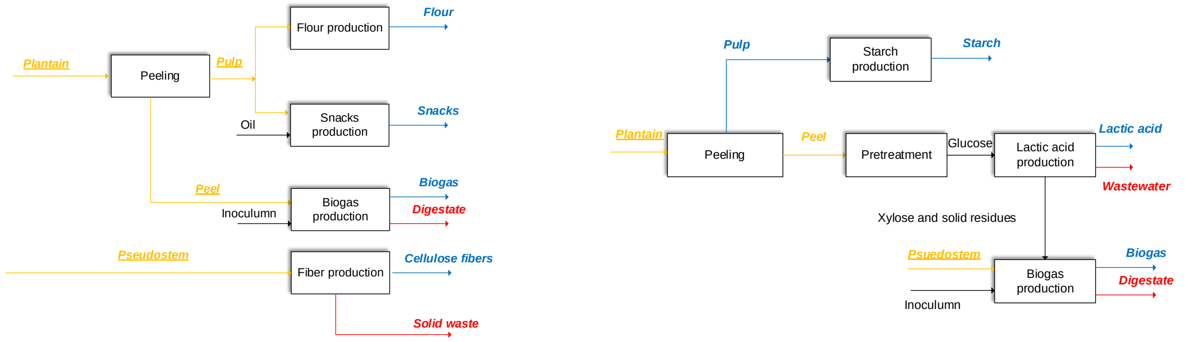
Plantain is considered the fourth most important crop globally, after wheat, rice, and corn. The annual world production of bananas and plantain is about 106.7 million tonnes (Ghag and Ganapathi, 2017). Banana comprised 70% of the total output, while plantain production is about 30%. However, large amounts of plantain are disposed of in landfills for not fulfilling the export standards. Indeed, about 24-40% of plantain is not commercialized and left in the field until decomposition (Rodríguez et al., 2020). Nevertheless, plantain has been researched as potential raw material to produce value-added products and other low-cost products such as animal feed, flour production, biogas, and bioethanol. Besides, this fruit is susceptible to entrepreneurship opportunities to improve rural people's quality of life. The uses mentioned above of plantain residues generated in the crop field conform to an alternative to valorize this fruit to produce energy vectors and marketable products without affecting the food security and involve high-energy intensive pretreatments. Instead, the use and valorization of this fruit is an entrepreneurship alternative to be considered a strategy to increase the quality of life of different regions in tropical countries. Therefore, this study aims to perform the economic analysis and performance evaluation of the bioethanol and plantain flour production using unripe plantain as raw material in terms of mass and energy indicators. In this way, the objective of this work is to peform the life cycle sustainability assessment of two plantain-based biorefineries considering a real context of an emerging industrial country like Colombia. This analysis is done to elucidate the potential implications of biorefineries implementation on a rural context.

The methodology applied to accomplish the objective of this work considered the following stages: **(i)** Conceptual design of two plantain-based biorefineries considering marketable products in the Colombian context and the technological readiness level of the country. **(ii)** Simulation of the proposed biorefineries using the Aspen Plus v9.0 simulation tool to obtain the mass and energy balances of the processes. The economic, environmental, and social analyses followed the life cycle assessment methodology proposed by ISO 14001. Then, a cradle to gate approach was defined as the system boundaries of the analysis. Thus, the main stages of plantain production and conversion in a process facility were considered. Information from direct interviews to farmers, machine-selling companies, and software were used as input data. **(iii)** The life cycle costing (LCC) considered expenses, costs, and incomes in the agricultural and productive stages of the proposed biorefineries using key information from a real crop in Colombia, quotations, and estimations made by the Aspen Process Economic Analyzer (APEA) software. The Life cycle costing has outputs such as costs per kg of plantain produced, capital and operational expenditures, and economic metrics such as net present value, internal rate of return, and payback period. **(iv)** The environmental life cycle assessment (E-LCA) considered all the inputs required to the crop, such as fertilizer and agrochemicals. The outputs of the ELCA are the water and carbon footprint of the plantain crop and the environmental impact caused by the implementation of the biorefineries considering midpoint impact categories such as climate change, eutrophication, and water depletion. Finally, **(v)** the social life cycle assessment (S-LCA) was done considering the main implications of the proposed biorefineries involving stakeholders, value-chain actors, and local community categories. Indicators were established by the Product Social Life Cycle Assessment database developed by GreenDelta.

The ***first stage*** (i.e., conceptual design of the biorefinery) was done considering the Montes de Maria region as a case of study due to the socio-economic detriment suffered due to the Colombian armed conflict in recent years. In this way, the proposed biorefineries can be seen as an alternative to evaluate the potential of the plantain crop in this region and identify some plantain processing alternatives. The first plantain-based biorefinery was to produce flour, snacks, biogas, and cellulose fibers (see **Figure 1a**). The second plantain-based biorefinery was designed to produce starch, lactic acid, and biogas (see **Figure 1b**). The ***second stage*** (i.e., simulation of the biorefinery) was done using the Aspen Plus simulation tool. The NTRL-RK thermodynamic method was selected to calculate the fugacity and activity coefficients of the components in the gas and liquid phase. Moreover, a mass flow rate of raw material (i.e., plantain) of 15 tonnes per day was proposed considering the plantain production of the Montes de Maria region. The ***third and four stages*** (i.e., economic, environmental, and social evaluations) were done using the APEA and SimaPro software, respectively. For the third stage, the mass and energy balances obtained from the second stage were used to size the equipment in the biorefineries. On the other hand, the raw materials, reagents, utilities, and labor cost was considered in the economic evaluation. The straight-line depreciation method was used, and an operation time of 8000 hours per year. Finally, the tax and interest rates used to perform the economic calculations were 12.1% and 32%, respectively (Solarte-Toro et al., 2021). Regarding the fourth stage, the environmental analysis was done considering 1 kg of product. Finally, the ***fifth stage*** (i.e., social analysis) was done using indicators such as fair salary, living wage, natural withdrawal, and carbon dioxide emissions (Eisfeldt and Ciroth, 2018).



a) First plantain-based biorefinery (Sc.1) **b)** Second plantain-based biorefinery (Sc.2)

Figure 1. Plantain-based biorefineries.

The results are analyzed considering the economic, environmental, and social perspectives. First, the LCC shows the low production costs associated with the plantain production process (i.e., agronomic stage) since Colombian farmers do not use several amounts of agrochemicals. The plantain production cost was 0.32 USD/kg considering labor and supplies. The economic performance of the first biorefinery was good because the payback period of the process was reached at six years with an internal rate of return of 19%. Nevertheless, the second biorefinery was not profitable since the capital expenditures of the lactic acid production process were higher to be covered by the product sales. Then, a scale analysis is recommended to find the minimum processing scale for economic feasibility. Regarding the environmental analysis, the life cycle assessment shows that the high-water consumption of the second biorefinery is one of the most important hotspots of the process. In addition, the plantain crop has a low carbon and water footprint compared to other crops such as orange and avocado. Finally, the social analysis demonstrated the serious difficulty of the farmers in the Montes de Maria region to implement some of the proposed alternatives. Then, integral support of government and private sector is recommended to increase the development of rural regions in emerging industrial countries like Colombia.

Conclusions.

The life cycle sustainability assessment of two plantain-based biorefineries was done to assess the potential of upgrading plantain in the Colombian context. Low-scale and low complexity processes are more feasible than biotechnological products. This statement was demonstrated through the comprehensive analysis of the three sustainability pillars.

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References.

Eisfeldt, F., Ciroth, A., 2018. PSILCA - A Product Social Impact Life Cycle Assessment database.

Ghag, S.B., Ganapathi, T.R., 2017. Genetically modified bananas: To mitigate food security concerns. Sci. Hortic. (Amsterdam). 214, 91–98. https://doi.org/10.1016/J.SCIENTA.2016.11.023

Rodríguez, L.J., Fabbri, S., Orrego, C.E., Owsianiak, M., 2020. Comparative life cycle assessment of coffee jar lids made from biocomposites containing poly(lactic acid) and banana fiber. J. Environ. Manage. 266. https://doi.org/10.1016/j.jenvman.2020.110493

Solarte-Toro, J.C., Ortiz-Sanchez, M., Restrepo-Serna, D.L., Peroza Piñeres, P., Pérez Cordero, A., Cardona Alzate, C.A., 2021. Influence of products portfolio and process contextualization on the economic performance of small- and large-scale avocado biorefineries. Bioresour. Technol. 342, 126060. https://doi.org/10.1016/j.biortech.2021.126060