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Perspectives of the Sustainability Assessment of Biorefineries

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The joint analysis of economic, environmental, and social aspects of biorefineries has been boosted in recent years. The sustainability assessment of biorefineries is considered a fundamental approach to determine the possible implementation of processes due to the inclusion of different stakeholders in the analysis. Few studies related to the sustainability of biorefineries have been reported due to the difficulty of including social aspects. Most of the studies related to the sustainability assessment of biorefineries do not report a sustainability framework. This fact decreases the comparison and reproducibility of the reported results. This paper gives some perspectives related to the sustainability assessment of biorefineries based on a short literature review. A methodological approach to define the sustainability framework to assess the three dimensions of sustainability is given as a tool to evaluate biomass upgrading processes and biorefineries. This proposed approach was applied to a case of study to valorize rejected unripe plantains in the Montes de Maria region, Colombia. The results show the sustainability of the sequential production of plantain flour and bioethanol using the whole unripe plantain (pulp + peel). A payback period of 3.5 y and the possibility to create more than 50 employees boost this process as a potential entrepreneurship alternative to be studied in a detailed way. However, the only production of plantain flour is recommended to decrease the environmental impact caused by the ethanol production process.

1. Introduction

Biomass has been categorized as a promising alternative to mitigate the environmental damage caused by the excessive exploitation of non-renewable energy sources. This renewable resource has been researched to obtain products involving experimental and theoretical approaches (Jaroenkhasemmeesuk et al. 2020). From this, stand-alone processing lines and more complex processes, so-called biorefineries, have been raised to upgrade different biomass sources (Ubando et al. 2020). These alternatives have been evaluated considering technical, economic, and environmental metrics. The level of the industrial implementation of bio-based processes still is low in comparison with the number of alternatives obtained during the conceptual design stage. The sustainability concept involves the holistic analysis of different dimensions to identify impacts associated with the implementation of a biorefinery. The sustainability assessment of biorefineries involves three dimensions related to economics, environment, and society (Malik et al. 2016). Several approaches involving the estimation of individual indicators and impact categories have been developed to analyze these dimensions (Bello et al. 2020). The evaluation of the social impact of biorefineries still is under development due to the lack of quantitative indicators (Cadena et al. 2019). One of the most common approaches to carry out a sustainability assessment is through the life cycle thinking approach. Those analyses combining the life cycle thinking methodology, and the three dimensions of sustainability are known as life cycle sustainability assessment (LCSA). In this way, the evaluation of the economic, environmental, and social dimensions is done applying the life cycle costing (LCC), environmental life cycle assessment (E-LCA), and social life cycle assessment (S-LCA) approaches. The individual analysis of the three dimensions of sustainability is another way to evaluate the sustainability of a biorefinery. The individual evaluation of the three dimensions of sustainability has been reported using different methodologies to evaluate them. Even so, the methodologies described are sometimes ambiguous and inconsistent, which decreases the understanding, reproducibility, and impact of the sustainability assessment (Mahbub et al. 2019). The lack of contextualized information (e.g., taxes, fuel costs, fertilizers, labor

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conditions) difficult the comparison of the results reported by different authors. Issues related to the integral and equal evaluation of the three dimensions of sustainability have been identified (Costa et al. 2019). In this way, one of the main problems to perform and compare different studies is based on the lack of a methodological guideline and a framework to perform a sustainability assessment. The purpose of this paper is to give some perspectives related to the sustainability assessment of biorefineries based on a systematic literature review. The sustainability assessment of rejected plantain fruits is presented as a case of study.

2. Sustainability assessment of biorefineries

A short literature review was done using a multidisciplinary internet database (i.e., Web of Science). The review was developed using a Boolean string to find peer-reviewed publications. The search was addressed to find those publications, including the analysis of the three dimensions of sustainability, considering the life cycle assessment perspective. The review was done searching the terms “Life cycle sustainability assessment of biomass conversion,” “Life cycle sustainability assessment of biorefineries,” and “Substantiality assessment of biorefineries.” The time period was defined from 2015 to the present time (mid - 2020) (Palmeros Parada et al. 2017). Gray literature was excluded and the query results were screened through title, abstract content, and keywords (Costa et al., 2019). The advantages and disadvantages of LCSA were elucidated.

2.1 Literature review: findings

The search in the Web of Science database resulted in a total of 84 papers. From these, 17 are classified as review papers, and 67 are classified as research papers. The publication tendency related to the analysis of the sustainability of bio-based processes has increased recently. Even so, the number of papers directly associated with the sustainability assessment of biorefineries was low. This trend can be attributed to the difficulty of setting the functional unit of the life cycle assessment in biorefineries since energy vectors and marketable products are generated. This trend can be explained considering the recent implementation of the social analysis of these facilities. Several papers have been dedicated to performing the social analysis of biorefineries in a particular way. The publication of papers based on the search criteria has been increased by 2 % or 3 %/y. The highest publication was 2019, with 17 publications. The same increase is expected to 2020 since the number of publications until mid of 2020 was ten papers. The publication shares per year were 2020 (16.95 %), 2019 (28.14 %), 2018 (20.34 %), 2017 (18.64 %), 2016 (15.93 %).

One of the strengths related to the sustainability assessment of biorefineries is the need to contextualize the process through the consideration of social and economic aspects. This contextualization gives to the analysis more validity at the time to be analyzed by decision-makers. Another advantage is related to the identification of hotspots of the productive chain since the feasibility of a biorefinery is directly associated with the way to supply the raw materials. Instead, the short literature review allowed the identification of four main aspects to be improved when making a sustainability assessment of a biorefinery. These aspects are (i) the sustainability framework, (ii) the approach to perform the sustainability assessment, (iii) data acquisition, and (iv) interaction between the sustainability dimensions. The strengths and weaknesses of the sustainability assessment of biorefineries are summarized in Table 1.

2.2 Sustainability framework

The first aspect of improving in the sustainability assessment of biorefineries is the framework definition. A sustainability framework refers to a way to organize thinking about sustainability as well as integrate dimensions, principles, and criteria to give a structured way to analyze the information (Bautista et al. 2016). In this way, a sustainability framework is related to the objective of the analysis, the way to evaluate each dimension as well as the metrics used to calculate the performance of social, economic, and environmental aspects (Finkbeiner et al., 2010). In most cases, the sustainability framework is not defined, which makes difficult the comparison of the results with similar studies.

There is no methodological guide that allows establishing the indicators to be used as performance metrics for each dimension. There is necessary to establish a sustainability framework before performing a sustainability assessment. In this way, a sustainability framework should involve at least the definition of the dimensions to be evaluated, the goal and scope of the analysis, the stakeholders involved, the way to perform the assessment of each sustainability dimensions as well as the metrics to be calculated. All the assumptions will be stated to give a better understanding of the sustainability analysis. Figure 1 presents a schematic representation of a methodological guideline to set a sustainiability framework.

Table 1: Strengths and weaknesses of the sustainability assessment of biorefineries.

Strengths	Weaknesses
• The sustainability assessment of biorefineries allows organizing a wide variety of information related to the process in terms of economic, social and environmental aspects. • Decision-makers can use the results of the sustainability assessment as support to define the implementation of a biorefinery • The inclusion of social, economic, and environmental aspects allows identifying hotspots of a bio-based productive chain • The sustainability assessment gives a better understanding of the real context where biorefineries are involved.	• The framework used to perform a sustainability assessment is often omitted in some publications, which difficult the comparison and reproducibility of the results. • There are several methodological approaches and metrics to analyze the three dimensions of sustainability, which difficult the comparison • The databases to perform an LCC and S-LCA do not have the same development as the databases used to carry out an E-LCA. • The integrated analysis of the effect of one dimension on the other requires further research and improvements.

Figure 1: A proposed methodological approach to defining a sustainability framework.

2.3 Approaches for biorefineries sustainability

There are different approaches to estimate the sustainability of biorefineries reported in the open literature. In most cases, the term LCSA is used to reference the sustainability assessment of a process. Several authors used this term without matter if the analysis of the three dimensions of sustainability is performed using the life cycle thinking approach or any other methodology (Matthews et al. 2019). The definition of the methodological approach (i.e., assumptions, values, indicators) to evaluate each dimension is a crucial step because this correct specification of the way to perform the evaluation of the economic, social, and environmental dimensions can derive in a good understanding of the sustainability assessment as well as impact directly in the reproducibility of the study. Costa et al. (2019) identified three main approaches to perform a sustainability assessment. The first one is the “conventional way,” which is to consider the sustainability assessment as the sum of the results of the LCC, E-LCA, and S-LCA. Another approach to estimating the sustainability is based on a single inventory for the three dimensions of sustainability.

2.4 Data acquisition

Data acquisition is a vital stage to perform a sustainability assessment since the global analysis of the process requires the specification of all inputs and outputs of the system and subsystems. The environmental dimension has a well-established series of databases introduced in software such as SimaPro or GaBi. These databases have been used to perform the analysis of biorefineries (Aristizábal-Marulanda et al. 2020a). The LCC and the S-LCA are not widely reported in the literature. LCC is challenging to be involved in the sustainability assessment of biorefineries due to the variation of the costs yearly (Costa et al. 2019). For this reason, different authors have opted for the use of cost indicators and profit indicators (Palmeros Parada et al. 2017). Instead, social databases are evolving to include more indicators and consider different stakeholders. For instance, the Product Social Impact Life Cycle Assessment (PSILCA) database involves five stakeholders (i.e., workers, local community, society, consumers, and value chain actors (Eisfeldt and Ciroth, 2018). The inclusion of this data to perform a sustainability assessment still is researched due to the single social analysis of a biorefinery that has not been well established (Ubando et al. 2020).

2.5 Integrated analysis

The last aspect of being improved when making a sustainability assessment is the integration of the three dimensions of sustainability. Most of the papers perform an evaluation of these dimensions, but the effects of

one dimension on the other are not analyzed. For instance, Aristizábal-Marulanda et al. (2020b) reported an inverse relationship between the economic and social dimensions since the increase of the processing scale affects the local community stakeholder. Valente et al. (2019) report a direct relation between these dimensions since more profits increase the workers' benefits. There is necessary to make a more in-depth analysis of the real interaction between the three sustainability indicators to elucidate

3. Case of study: Sustainability assessment of the rejected unripe plantains valorization

Rejected unripe plantains are a potential raw material to obtain several value-added products and energy vectors. This agricultural waste can boost the economic growth of producer zones through the commercialization of marketable products at the local, regional, and national levels. In this way, plantain flour and bioethanol can be produced simultaneously applying the biorefinery concept. The sustainability assessment of this process has not been reported previously. This case of study presents the sustainability assessment of a biorefinery dedicated to producing plantain flour and bioethanol using rejected unripe plantain as raw material.

3.1 Sustainability framework

Alonso-Gómez et al. (2020) reported two ways to produce plantain flour and bioethanol under a biorefinery scheme. In this analysis, the whole plantain (i.e., pulp + peel) is used to produce both plantain flour and bioethanol in a sequential process. For this, 25 % of the plantain flour is used to produce bioethanol. The sustainability assessment is contextualized in the Colombian context, specifically in the Montes Maria region, which is one of the most affected rural zones by the armed conflict of recent years. Figure 2 presents the sustainability framework defined for this evaluation.

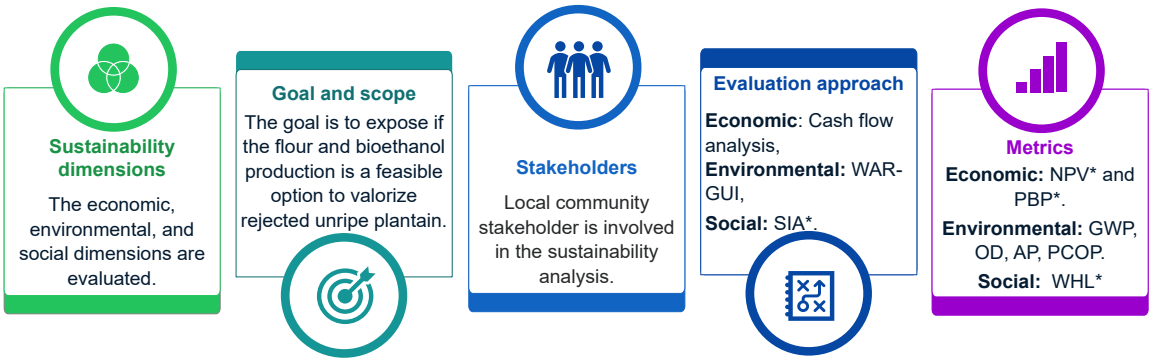


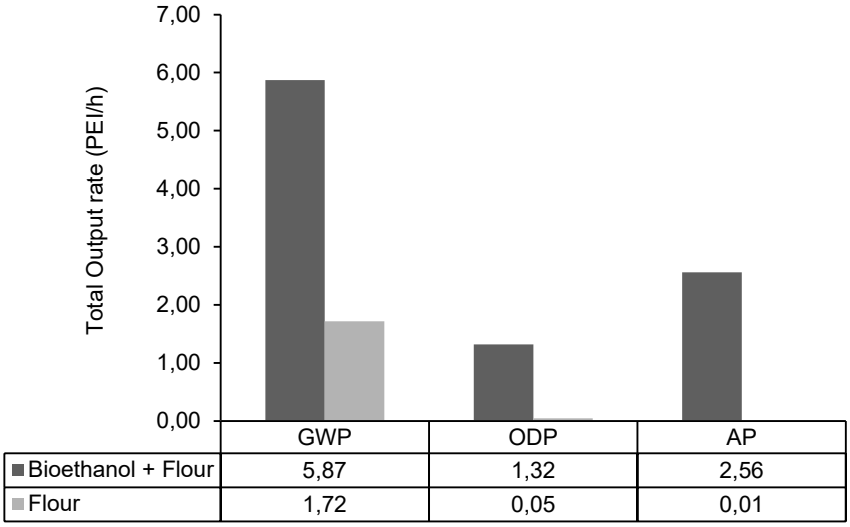
*Figure 2: Proposed sustainability framework to assess the feasibility of the plantain flour and bioethanol production using rejected unripe plantain. *SIA: Social impact assessment methodology, NPV: Net present value, PBP: Payback Period, GWP: Global Warming Potential, OD: Ozone Depletion, AP: Acidification Potential, PCOP: Photochemical Oxidation Potential, and WHL: Workforce hired locally.*

3.2 Methodology

Alonso-Gómez et al. (2020 have reported the economic assessment of the proposed process valorization. This data is used to be included as a result of the economic dimensions. The environmental and social assessment of this scenario is not reported in the open literature. The methodological descriptions of the environmental impact assessment and social impact assessment are presented. A gate – to – gate approach was considered as the system boundaries to analyze the three dimensions of sustainiblity. The environmental assessment of the plantain flour and bioethanol production were carried out using a systematic approach to determine the potential environmental impact (PEI) proposed by Young et al. (2000). The Waste Reduction Algorithm (WAR), developed by the National Risk Management Research Laboratory from the USA Environmental Protection Agency (EPA), was used. The WAR software performs the PEI impact, considering the global atmospheric category. This approach involves the calculation of the global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), and photochemical oxidation potential (PCOP) as impact categories (Rincón et al. 2014). The input data to the WAR software are the mass and energy balances of the process reported by Alonso-Gómez et al. (2020). The social impact assessment of the process was performed considering only the local community stakeholder, and the specific indicator workforce hired locally due to this indicator can give an estimate of the number of employees generated by the productive process. The workforce was calculated considering the number of persons required to perform each unit operation involved in the biorefinery.

3.3 Results

The estimation of the economic metrics of the plantain flour and bioethanol production allows determining the feasible implementation of this process in the Colombian context. The project has a PBP of 3.5 y and a positive NPV of 7.93 M.USD The proposed process seems to be a feasible option from an economic point of view. These results are attributed to the high market price of plantain flour (i.e., 2.3 USD/kg). Regarding to the total capital investment, the bioethanol plant has more than 65 % of the capital investment and does not contribute more than 40 % of the plant gross incomes. The bioethanol production using plantain flour as raw material is not the best option since this process has a low benefit-cost ratio. In this way, the bioethanol production process should be avoided from the biorefinery and use 100 % of the plantain flour to commercialization. This analysis is in agreement with the results reported by Alonso-Gómez et al. (2020).
The environmental analysis of the proposed biorefinery allows identifying a high contribution of to the GWP impact category due to the CO_2 emissions derived from the use of fossil fuel to produce the required utilities of the process. The AP impact category also presents a high impact in comparison to the other categories. This is explained by the release of chemical substances able to produce acid rain, such as NOx. A comparison with the stand-alone production process was done to see the better performance of this option respect to the sequential flour and ethanol production. Figure 3 presents the results of the WAR analysis.



	GWP	ODP	AP
Bioethanol + Flour	5,87	1,32	2,56
Flour	1,72	0,05	0,01

Figure 3: Results of the WAR analysis.

Finally, the social impact assessment was done considering the number of employees. In this way, literature data was reviewed in order to determine the number of employees required to produce plantain flour and bioethanol. The plantain flour production has different stages considering drying, washing, cutting, and milling. The plant capacity proposed by Alonso-Gómez et al. (2020) is able to process 5.5 t/h (wet basis). This high amount of plantain should be prepared for the process.The number of employees required in the plant is 60 workers. This high amount of employees is considering the low technological development of the plant to ensure a low capital investment. The number of employees required in a bioethanol plant is about 12 employees (i.e., three workers per shift). In this way, the total number of the workforce hired locally is 68 employees. Finally, four supervisors should be hired. From the three dimensions assessment, the bioethanol production process seems not to be the best alternative to complement the production of plantain flour using rejected unripe plantains. The stand-alone production of plantain flour is the most sustainable alternative to valorize rejected unripe plantains since high incomes, low environmental impact, and high social performce could be demonstrated.

4. Conclusions.

The sustainability assessment of biorefineries still is under development since it is necessary to improve several factors related to the statement of the sustainability framework, the way to assess each dimension, increase the databases with social and economic data, and improve the integral evaluation of the sustainability dimensions. Several studies have tried to improve these aspects, including different methodological approaches. Even so, there is necessary further research and development in this field. In this work, five steps are recommended to

define the sustainability framework before evaluating a biorefinery. These steps are based on the main findings of the literature review. Regarding the case of the study presented, the production of stand-alone plantain flour is a more sustainable option to increase the socio-economic and environmental development of rural zones since this product can generate high incomes and job opportunities.

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