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Sustainability Assessment of Food Waste Biorefineries as the Base of the Entrepreneurship in Rural Zones of Colombia

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Abstract: The sustainability of food value chains is affected by the large amounts of waste produced with a high environmental impact. Food waste valorization applying the biorefinery concept has emerged as an alternative to reduce the generation of greenhouse gases and to promote the socio-economic development of value chains at local, regional, and national levels. This paper analyzes the sustainability of food waste biorefineries designed for boosting rural economic development in Colombia. These biorefineries were designed following a strategy based on a portfolio of bio-processes involving fractions based on the composition of the raw materials. The valorization of six food residues produced in three representative rural areas of Colombia (i.e., Chocó, Caldas, and Sucre) was analyzed. Acai, annatto, sugarcane bagasse, rejected plantain and avocado, and organic kitchen food waste (OKFW) were selected as food wastes for upgrading. The biorefinery design strategy comprised five steps for filtering the most promising bioprocesses to be implemented. The OKFW was analyzed in detail, applying the design strategy to provide a step-by-step guide involving a portfolio of bioproducts, the technological maturity index, and the socio-economic context. This strategy implementation for OKFW valorization resulted in a scenario where biorefineries with levulinic acid production were the most feasible and sustainable, with high techno-economic performances and low environmental impacts. For the valorization of the other food residues, the processes with the greatest feasibility of being implemented in rural areas were bioactive compounds, oil, flour, and biogas production.

Keywords: food waste; biorefineries; sustainability assessment; design strategy; entrepreneurship

1. Introduction

Food residues are one of the most important issues in the world due to the high per capita residues generated [1]. Developed and developing countries are making efforts to mitigate food residue generation by implementing strategies and policies [2]. A food supply chain (FSC) generates food losses (FLs) and food waste (FW) [3]. FLs obtained during the agricultural and farming production, post-harvest, handling, slaughter, and storage, and process distribution and transformation stages can be grouped as agronomic losses (ALs) [4]. These wastes are generated at a single FSC location. For example, the FSC for fruit production has, in the first three stages, the same location as the crop or is in neighboring areas. In the fruit agricultural production stage, stems, leaves, roots, flowers, and fruits are generated with low-quality standards (overripe) [5]. On the other hand, the post-harvest, storage, process distribution, and transportation stages produce low-quality standard fruits. FLs generated during the processing, packaging, and distribution stages can be grouped as agroindustry losses (AgLs) [6]. In the case of the FSC for fruit, residues such as peel, seeds, liquids, and solid residues are generated during the above-mentioned stages. Finally, the FW obtained in the last stages of an FSC can be classified as manufacturing and domestic food waste [7]. This type of waste contains a mixture of agronomic and agroindustrial products such as vegetables, fruits, farming products, or processed products [8]. The main characteristic of this waste is its non-standard composition [9]. Regarding the above information, two characterizations can be approached according to the FW composition. Agronomic and agroindustrial residues are classified as standard food waste. On the other hand, manufacturing and domestic food waste are considered to be non-standard food waste [10].

Sustainability has been defined as the perfect balance between the economic, environmental, and social aspects of a system, product, or process [11]. This concept has been applied to describe the performances of different food residue upgrading alternatives to obtain value-added products and energy vectors at the laboratory, pilot, bench, or industrial scale [12]. Food residue valorization is the base for closing the loop in several value chains since the residues produced in one link (e.g., food losses) can be used to produce marketable products with commercial value and to move forward to carbon neutrality [13]. Moreover, FW valorization is in line with the sustainable development goals (SDGs) proposed by the UN since actions to reduce and upgrade FW are being researched and implemented at different scales [14]. SDG 12, "Sustainable production and consumption", can be accomplished through waste upgrading since unsustainable patterns (e.g., excessive reliance on natural resources and high per capita food residue production) can be reduced without affecting the dynamics of any value chain. Then, the integral FW upgrading plays a key role in developing a more sustainable production–consumption dynamics since reducing and valorizing waste streams results in more income (i.e., fewer disposal expenses) and lower environmental impacts. In this way, FWs should be upgraded by applying the biorefinery concept as a strategy to increase the product portfolio of an FSC [15].

Biorefineries are complex systems where a biomass is processed to obtain a portfolio of value-added products and energy vectors after integral processing that applies biotechnological, thermochemical, and physic-chemical processes [16]. FLs and FWs have been studied as raw materials to be valorized in conceptually designed biorefineries [17]. There are several reports in the literature of techno-economic (TEA) and environmental analyses. Nevertheless, most studies have not involved other crucial factors for designing more reliable and feasible processes. Factors such as (i) context (i.e., specific territory knowledge), (ii) processing scale, (iii) logistics and location, (iv) technological readiness level (TRL), (v) local and regional market needs, and (vi) national and international policies must be involved to propose more accurate processes for the reality of the situation [18]. These factors are important when designing biorefineries since the portfolio of products and biorefinery configuration can change depending on the biomass fractions and context.

Developed countries (e.g., Germany, Italy, and the United States of America) have great potential for establishing bioeconomies through the implementation of large-scale biorefineries to produce value-added products such as biosurfactants, organic molecules, and pharmaceuticals [19]. Large-scale processes require adequate infrastructure and a high industrialization level [20]. These processes are favored by the economy–scale concept. Nevertheless, their most important disadvantages are their raw material acquisition and logistics [21]. Developing countries (e.g., Latin American countries) have a great potential to develop a rural bioeconomy based on implementing small-scale biorefineries since these processes do not require a high industrialization level. Small-scale biorefineries must be addressed to produce local products and energy vectors [22]. The starting point to develop these processes are rural areas in developing countries since a large amount of FL is produced [23]. Several efforts to involve rural zones as the bases for establishing bioeconomies have been reported in the open literature. For instance, Solarte-Toro et al. [24] reported different small-scale configurations to upgrade avocado (*Persea americana var. americana*) residues into local marketable products such as avocado oil and guacamole. Moreover, Serna-Loaiza et al. [25] published small-scale processes addressed to upgrade cocoyam (*Xanthosoma sagittifolium*) into local products such as animal feed and starch. These efforts have demonstrated the great potential of FLs as raw materials to contribute to the socio-economic growth of a region.

Regarding the potential of small-scale biorefineries to improve the socio-economic conditions of a region, these facilities can be considered as entrepreneurship since small-scale processes can generate new job positions and contribute to decreasing the number of informal jobs. Moreover, implementing entrepreneurships based on biomasses in rural zones can establish rural bioeconomies. Thus, FW upgrading in small-scale biorefineries is the first step towards the sustainable development of a region. The objective of this work was to evaluate the potential for upgrading different FWs produced in representative rural zones of Colombia for a series of marketable products and energy vectors. A design methodology based on selecting the bioproducts portfolio reported by Ortiz-Sanchez and Cardona Alzate [26] was applied. The studied FWs in this manuscript come from avocado, plantain, acai, brown sugarcane, annatto, and OKFW.

2. Methodology

In Colombia, there are different rural areas dedicated to agricultural activities with problems such as armed conflicts, low production yields, and high waste generation. In this work, the sustainability analysis of food waste biorefineries was conducted considering three rural zones of Colombia. The rural zones analyzed are located on the north coast (close to Caribbean Sea), the Montes de María in the Sucre department; the west coast (close to Pacific Ocean), the Unión Panamericana, Quibdó, and Bojayá in the Chocó department; and Samaná, in the Caldas department. The most representative food crops of the analyzed zones are avocado, plantain, açai, annatto, and sugarcane. Figure 1 shows the three zones selected and the raw materials analyzed in this paper. The raw materials were classified into FLs and FWs. The three rural regions analyzed in this manuscript represent three different ecosystems and thermal floors (i.e., different types of soil, crops, agricultural practices, productivities, and yields) that allowed for the analyses of various raw materials with diverse chemical compositions. In this sense, raw materials such as achiote and acai allow for valorizing extractive fractions to obtain bioactive compounds (e.g., colorants). Plantain and avocado allow for the analysis of valorization routes for producing foods such as flour and avocado oil. Finally, OKFW, due to its content of fats, pectin, starch, fiber, and extractives, requires more complex recovery routes to be proposed. In countries located in the tropics, this type of analysis demonstrates how FW can be valued in different ecosystems. The sustainability of the biorefineries was analyzed considering the methodology reported by Ortiz-Sanchez and Cardona Alzate [26].

In Sucre (zone 1), the valorization of rejected avocado (*Persea americana* sp.) and plantain (*Musa paradisiaca* sp.) was analyzed. Raw material flows of 150 kg/h of rejected avocado and 2145 kg/h of rejected plantain were considered. The flows were equivalent to 100% of the rejected avocado and plantain generated in the rural zone of Montes de María. In Chocó (zone 2), the use of non-marketed açai (*Euterpe oleracea*) and waste food additives generated from the extraction of annatto dye (*Bixa orellana* L.) were evaluated.

The raw material flows for the analysis of the biorefineries were 13.5 kg/h of açai and 51.8 kg/h of annatto. The flows were selected considering 50% of the açai and annatto production in Unión Panamericana, Quibdó, and Bojayá from Chocó. Finally, sugarcane bagasse (*Saccharum officinarum*) and OKFW were analyzed in Caldas (zone 3). The sugarcane milling generated the bagasse corresponding to 44% *w*/*w* of the raw material. This work analyzed the valorization of 50% of the sugarcane bagasse generated in zone 3 (80.4 kg/h). OKFW was considered an optional source of raw material in zone 3 due to its current use of sugarcane bagasse. Given the impossible standardization of the OKFW, a model based on Colombian food consumption was used. In this case, a use of 40% of the OKFW generated in zone 3 (93.2 ton/h) was analyzed. The valorization of FL analyzed in this work was carried out considering small-scale biorefineries. On the other hand, the valorization of FW was analyzed considering high-scale biorefineries.

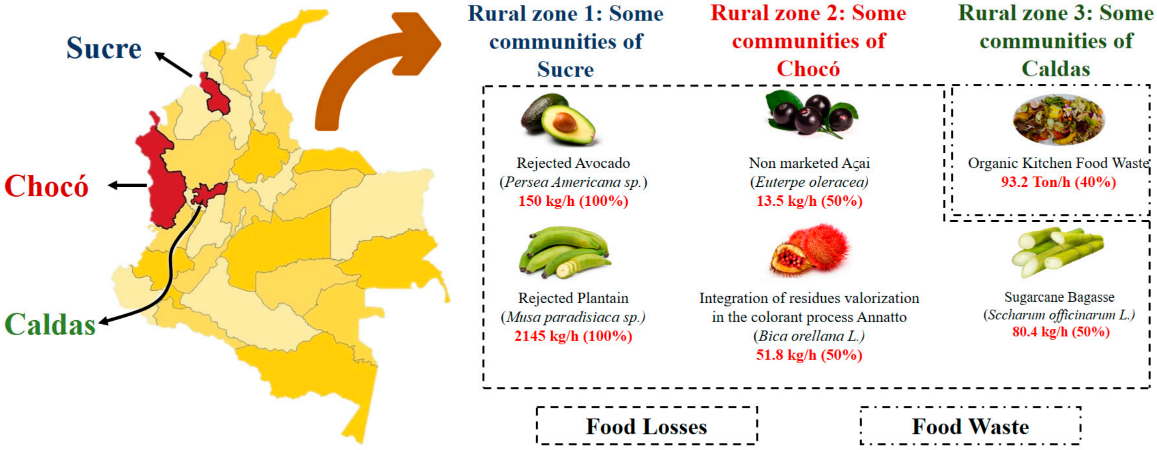

Figure 1. Zones and raw materials selected for the food waste biorefineries analysis.

2.1. Sustainability Analysis of Biorefineries—Design Strategy of the Biomass Valorization

The sustainability analysis of the food waste biorefineries was carried out considering the strategy reported by Ortiz-Sanchez and Cardona Alzate [26]. This work defined a design and evaluation strategy considering different biomass processing routes based on chemical composition. The strategy comprises five steps where filtration of the bioprocesses is developed as a function of each fraction of the raw material (i.e., cellulose, hemicellulose, lignin, starch, pectin, extracts, and fats). The steps of the design strategy are presented in Figure 2.

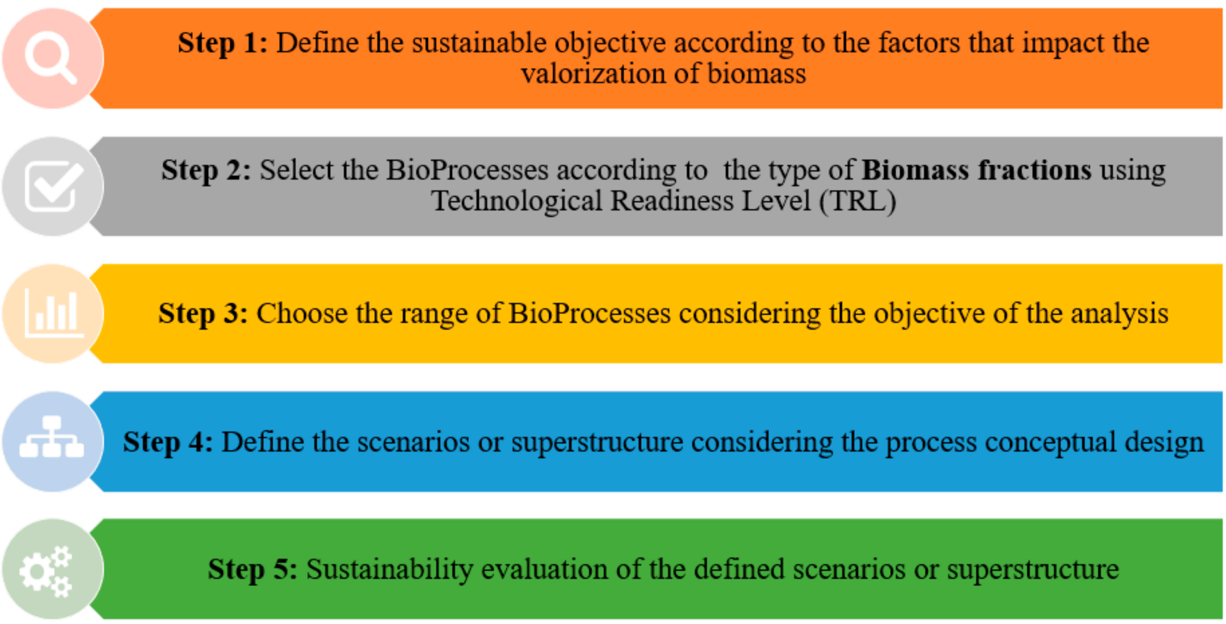

Figure 2. The steps of the design strategy for analyzing the sustainability of the biorefineries.

The first step in the design strategy is to define the sustainability objective considering limiting factors such as production chain, scale, technological context, and product type to be obtained. In this step, it is necessary to be clear about the biomass uses in the specific context. The second step is to select the bioprocesses according to the sustainability objective. In this step, the TRL of the bioprocesses must be analyzed. Therefore, the selection of bioprocesses is considered as the first filter. The third step is the second bioprocess filter. This second filter is based on the sustainability objective (technical, economic, or environmental). If the sustainability objective is to seek the economic and environmental viability of biomass uses, the bioprocesses must be defined with favorable economic and environmental indicators. Step four defines the scenarios or superstructure according to the selected bioprocesses. Scenarios must be considered using the conceptual design methodology. Finally, step five evaluates the scenarios or superstructure considering the technical, economic, or environmental indicators.

2.1.1. Step 1: The Sustainable Objective

The sustainability objective was to define the best route for FL and FW valorization in economic and environmental terms as the basis of entrepreneurship. The main limiting factors for the valorization of FL and FW under the biorefinery concept are the low technological level (zones) and low raw material flows (low-scale biorefineries). These considerations limit the type of bioprocess that can be implemented in the study zones. For this reason, processes with high TRLs and easy-to-market products should be considered.

2.1.2. Step 2: First Filter of the Bioprocesses According to the TRL

The second step of the biorefinery design strategy was carried out considering the portfolio reported by Ortiz-Sanchez and Cardona Alzate [26]. Table 1 shows the bioprocesses considered in the portfolio.

Table 1. Bioprocesses portfolio considered to upgrade raw material fractions. Based on [26].

Raw Material Fraction	Bioprocesses	Bioproducts	Technology
Extractives	2	Bioactive compounds	Agitated solvent extraction Supercritical fluid extraction with carbon dioxide
Fats	4	Essential oil and oil Biodiesel	Steam distillation and hydrodistillation Extrussion Trasesterification
Cellulose	9	Glucose platform Ethanol and ABE * Lactic acid PHB ** Itaconic acid Polylactic acid	Catalytic and enzymatic hydrolysis glucosa production Fermentation—*Saccharomyces cerevisiae* *Clostridium acetobutylicym*, *Lactobacillus casei*, *Bacillus megaterium*, and *Aspegillus terreus* Catalytic upgrading
Hemicellulose	4	Xylose platform Furfural Xylitol Pentane	Acid hydrolysis Catalytic upgrading Fermentation—*Candida giillermondii*
Lignin	4	Soda lignin Organosolv lignin Kraft lignin Vainillin and vanilic acid	Alcaline pretreatment Organosolv pretreatment Kraft process Catatytic upgrading
Pectin	4	Pectin Mucic acid Galacturonic acid and sugars platform	Acid hydrolysis Fermentation Enzymatic hydrolysis

Table 1. *Cont.*

Raw Material Fraction	Bioprocesses	Bioproducts	Technology
Starch	2	Glucose plarform Flour	Enzymatic hydrolysis Extraction
All fractions	6	Biogas Biomethane Syngas Hydrogen Heat and power	Anaerobic digestion Pressure swing absorption Chemical absorption Gasification Water gas shift Combustion and cogeneration

* Acetone, Butanol and Ethanol, ** Polyhydroxybutyrate.

The selection of the bioprocesses was carried out considering a TRL implementation level. This was completed based on the technological context of the zone. The selection of the bioprocesses was developed considering the raw material fractions shown in Table 1 (in the Figure 3 of the reference (Ortiz-Sanchez and Cardona Alzate [26]), the TRL for these technologies is described). Thus, the chemical characterizations of the raw materials were taken from available literature reports. Table 2 shows the chemical compositions of the raw materials used in the analyzed zones.

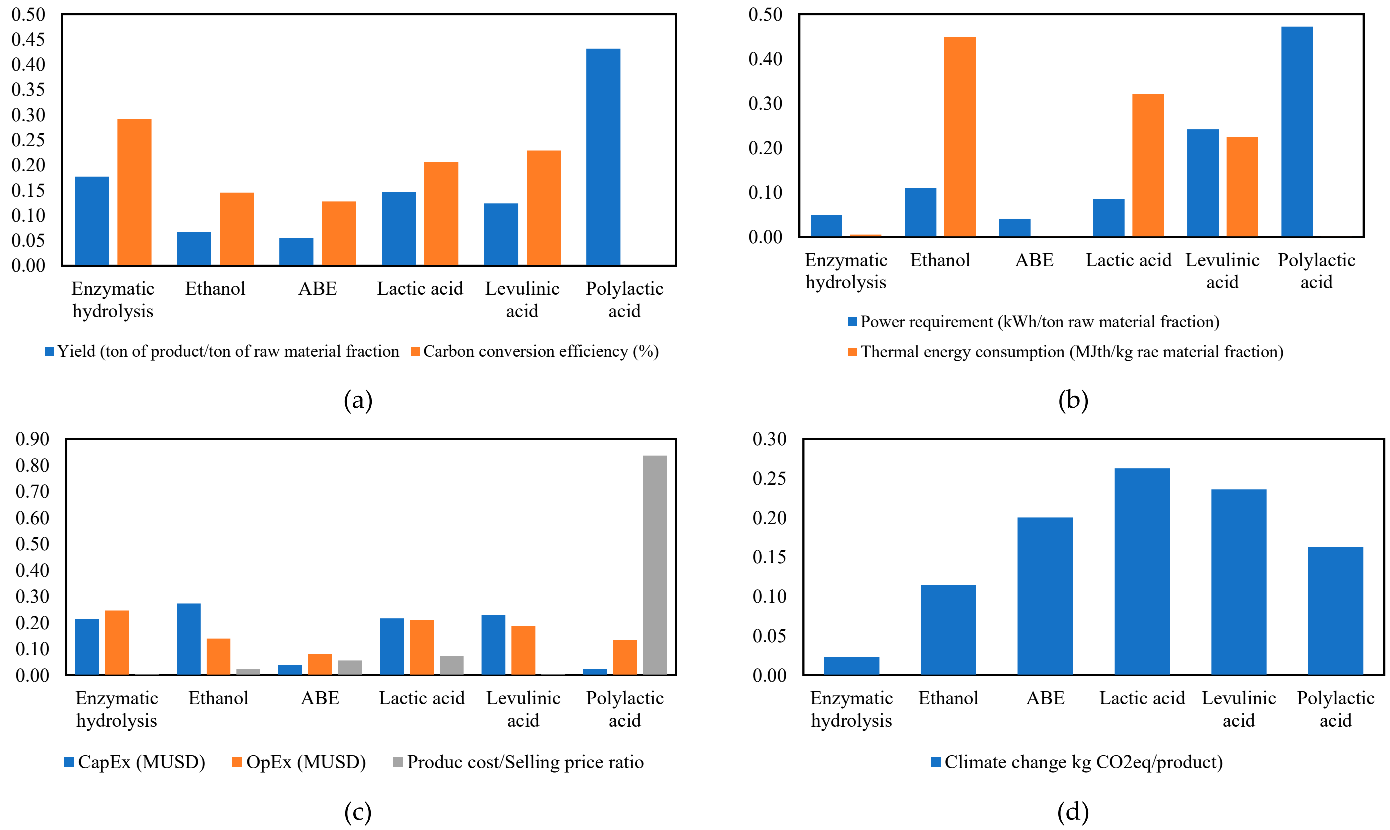

Figure 3. Indicators for cellulose fraction valorization: (**a**) mass indicators; (**b**) energy indicators; (**c**) economic indicators; and (**d**) environmental indicator. Based on [26].

The technical, economic, and environmental indicators of the bioprocesses presented in Table 1 were calculated considering the fermentable sugars that could be obtained from the cellulose fraction (for the methodology details, please see Figure 4 in the study by Ortiz-Sanchez and Cardona Alzate [26]). For the hemicellulose fraction, the bioprocesses for obtaining furfural, xylitol, and pentane were obtained from xylose. Additionally, the production of galacturonic acid and mucic acid was completed based on the pectin fraction.

Table 2. Chemical characterization of the raw materials used in the zones in Colombia.

Item	Food Losses									Food Waste
	Zone 1 [27,28]					Zone 2 [29]			Zone 3	
	Avocado		Plantain			Annatto	Açai		Sugarcane Bagasse [30]	OKFW [18]
	Peel	Seed	Peel	Peel and Pulp	Pseudosteam	Seed	Seed	Pulp		
Share of fruit (% *w*/*w*)	13.03	15.33	28.65	100	N.A.		90	10	N.A.	N.A.
Chemical composition (% *w*/*w*, dry basis)										
Moisture *	13.17	11.09	87.16	71	82.74	40.01	31.26	89.63	21.83	79.13
Extractives	28.09	32.01	31.58	42.41	46.80	27.00	21.36	N.R.	11.36	21.13
Cellulose	14.21	22.50	11.04	11.96	18.78	17.85	12.49		43.42	19.91
Hemicellulose	9.88	15.64	9.66	18.95	16.12	10.76	40.85	16.81	20.20	5.17
Lignin	8.26	10.35	7.42	14.32	4.01	13.21	15.23		22.61	13.83
Pectin	N.R.	N.R.	N.R.	N.R.	N.R.	15.18	N.R.	N.R.	N.R.	5.28
Protein	N.R.	N.R.	N.R.	N.R.	N.R.	8.26	N.R.	6.01	N.R.	N.R.
Starch	26.10	1.66	29.17	N.R.	N.R.	N.R.	N.R.	N.R.	N.R.	26.03
Fats	10.42	14.44	N.R.	N.R.	N.R.	2.62	2.85	73.99	N.R.	5.39
Ash	3.04	3.40	11.13	12.36	14.28	5.11	7.22	3.20	2.41	3.26
TOTAL	100	100	100	100	100	100	100	100	100	100
Total and volatile solids ** (% *w*/*w*)										
Total solids	89.92	43.99	90.95	89.43	88.05	94.5	N.R.	25.4	91.6	27.98
Volatile solids	87.91	42.40	71.13	75.31	76.99	90.3	N.R.	24.3	88.2	25.61

N.A., not applicable; N.R., not reported; *, raw moisture content; **, total and volatile solids measured based on raw materials as received.

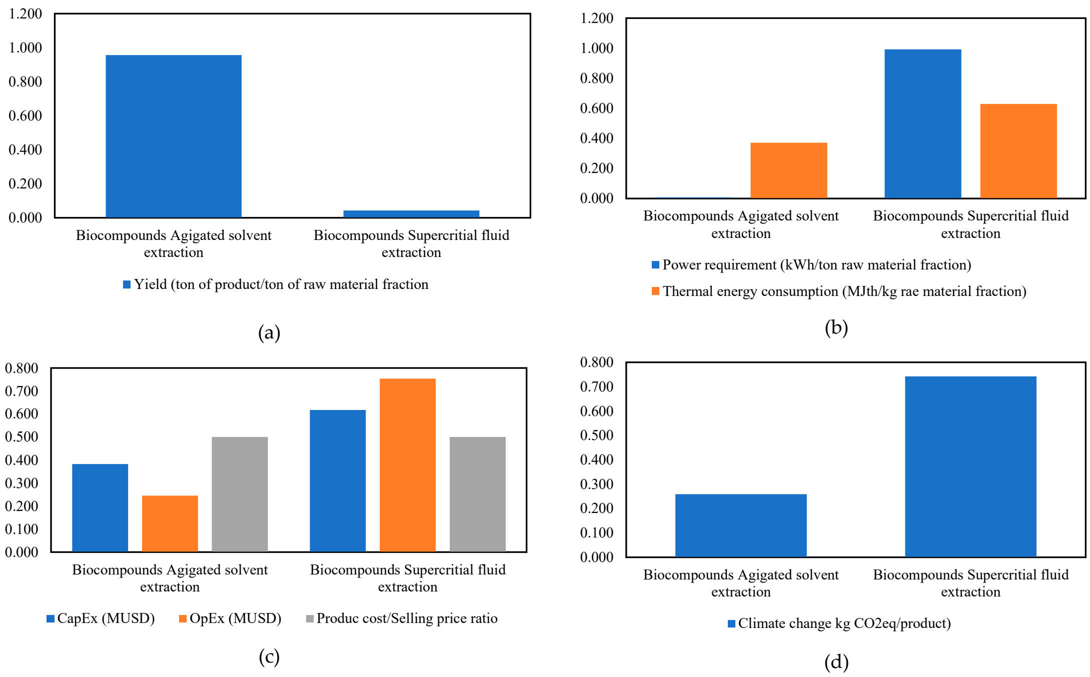

Figure 4. Indicators for the extractives fraction valorization: (**a**) mass indicators; (**b**) energy indicators; (**c**) economic indicators; and (**d**) environmental indicator. Based on [26].

2.1.3. Step 3: Second Filter Based on the Technical, Economic, and Environmental Indicators

Once the bioprocesses were selected according to the TRL, the second filtration step was carried out considering the sustainability objective. The bioprocess portfolio reported by Ortiz-Sanchez and Cardona Alzate [26] presented technical, economic, and environmental indicators for the bioproducts presented in Table 1. The technical indicators considered in the portfolio were yield (ton of product/ton of raw material fraction), carbon conversion efficiency (%), power requirements (kWh/ton raw material fraction), and thermal energy consumption (MJth/ton raw material fraction). The thermal energy consumption for the bioprocesses presented in Table 1 indicate the distribution of utilities (i.e., cooling water, low-pressure steam, medium-pressure steam, and high-pressure steam). The economic indicators were capital expenditures and operational expenditures. Finally, the environmental indicators referred to climate change (kg CO_2 eq/product). The second bioprocess filter was carried out according to the sustainability objective for food waste biorefineries considering the lowest values of capital costs and operational costs and the lowest environmental impact.

2.1.4. Step 4: Biorefineries Scenarios

The biorefinery scenarios were proposed considering the bioprocesses selected up to the previous step. In this step, the conceptual design methodology reported by Cardona et al. [16] was considered. The conceptual design methodology encompassed the use of hierarchy and process sequencing. The hierarchy concept implied the hierarchical decomposition of the fractions of the raw materials. On the other hand, sequencing defined the logical synthesis of the bioprocesses.

2.1.5. Step 5: Biorefinery Analysis

Based on the biorefinery scenarios, an economic and environmental evaluation was completed. In economic terms, the analysis of the biorefineries was carried out considering the net present value (NPV) of the process. The methodology described by Towler and Sinnott [31] was considered. Operational expenditures and capital expenditures were obtained from the bioprocess portfolio reported by Ortiz-Sanchez and Cardona Alzate [26]. In addition, the economic assessment of the biorefinery was completed considering the straight line as the depreciation method. Moreover, a continuous operation was assumed (i.e., 8000 h per year). Then, three (3) shifts were required. The project lifetime was presumed to be 20 years.

3. Results and Discussion

The methodological steps of the biorefinery design strategy are presented in detail using OKFW as example. The results obtained for the other raw materials are presented and avoid a deeper explanation following the steps described in the methodology section. Nevertheless, the economic analyses of the small-scale biorefineries are described and analyzed.

3.1. Results for OKFW Valorization Applying the Design Strategy

3.1.1. Step 2: Results of First Filter of Bioprocesses

The TRL was selected as the starting point to specify a preliminary list of bioprocesses for upgrading each fraction of the raw material (i.e., OKFW). In this case, the biorefineries should be proposed to involve bioprocesses with a TRL value of between seven and nine (i.e., system prototype to system proven in an operational environment) since the process objective was addressed to establish reliable and feasible entrepreneurships. Then, those bioprocesses with TRLs higher than seven were selected. Table 3 presents the options available for upgrading the raw material into a series of value-added products and energy vectors.

The analysis of the raw material chemical composition serves as the basis for selecting the most relevant bioprocesses to be involved in the process configuration. For instance, OKFW has a low content of pectin and fats (<10% *w*/*w*). Therefore, an upgrading of these fractions is not suitable since low yields would be obtained and higher capital costs would be required. Therefore, the bioprocesses addressed to upgrade these fractions were not considered. In addition, the physical characteristics of the raw materials played a key role when selecting the valorization route for all fractions together. Indeed, high moisture content, as in the case of the OKFW, makes such a raw material unsuitable for thermochemical processing (i.e., gasification and combustion). Thus, these bioprocesses should not be considered since high energy must be supplied to reduce the moisture content, affecting the global energy balance of the process. Once this specification related to the raw material composition was obtained, a list of 15 bioprocesses was established for upgrading the cellulose, hemicellulose, lignin, and extractives fractions. Products such as levulinic acid, butanol, polylactic acid (PLA), lignin, xylose, and biogas constituted options for upgrading OKFW. Nevertheless, a second filter needed to be applied to define the most promising alternatives to be implemented based on technical, economic, and environmental indicators.

Table 3. List of selected bioprocesses for raw materials upgrading (e.g., for OKFW).

Fraction	Bioprocess	Bioproduct	TRL *
Cellulose	Enzymatic hydrolysis	Glucose platform	9
	Fermentation	Ethanol	9
	Fermentation	Butanol	8
	Fermentation	Lactic acid	9
	Catalytic upgrading	Levulinic acid	9
	Catalytic upgrading	Polylactic acid	9
Hemicellulose	Acid hydrolysis	Xylose platform	9
Lignin	Alkaline pretreatment	Soda lignin	9
	Organosolv pretreatment	Organosolv lignin	8
	Kraft/pulping	Kraft lignin	9
Extractives	Agitated solvent extraction	Bioactive compounds	9
	Supercritical fluids extraction	Bioactive compounds	8
Fats	Steam distillation	Essential oil	9
	Hydrodistillation	Essential oil	9
	Extrusion	Oil	9
	Transesterification	Biodiesel	9
Pectin	Enzymatic hydrolysis	Galacturonic acid	9
	Enzymatic hydrolysis	Glucose platform	9
	Starch production	Starch	9
All fractions	Anaerobic digestion (AD)	Biogas	9
	AD plus pressure swing absorption	Biomethane	9
	AD plus chemical absorption	Biomethane	9
	Gasification	Synthesis gas	9
	Cogeneration	Heat and Power	9

*, based on Figure 4 in the study by Ortiz-Sanchez and Cardona Alzate [26].

3.1.2. Step 3: Results of Second Filter According to the Technical, Economic, and Environmental Indicators

The second filter applied to the selected bioprocesses in Figure 2 was completed considering technical, economic, and environmental indicators. The indicators values for the fractions defined in step 2 are presented in Table 4. The economic indicators were calculated considering the OKFW flow.

Table 4. Technical, economic, and environmental indicators for each raw material fraction [26].

Fraction	Bioprocesses	Technical Indicators				Economic Indicators			Environmental Indicators
		Mass Indicators		Energy Indicators					
		Yield (Ton of Product/Ton of Raw Material Fraction	Carbon Conversion Efficiency (%)	Power Requirement (kWh/Ton Raw Material Fraction)	Thermal Energy Consumption (MJth/kg Raw Material Fraction)	CapEx (MUSD)	OpEx (MUSD)	Product Cost/Selling Price Ratio	Climate Change kg CO_2 (eq/product)
Cellulose	Enzymatic hydrolysis	0.8	92.6	1.8	0.73	132.87	43.92	0.21	0.28
	Ethanol	0.3	46.2	4	61.9	170.29	24.87	1	1.38
	ABE	0.25	40.51	1.5	0.007	24.82	14.32	2.41	2.41
	Lactic acid	0.66	65.75	3.1	44.3	134.74	37.70	3.11	3.16
	Levulinic acid	0.56	72.75	8.8	31	143.17	33.42	0.2	2.84
	Polylactic acid	1.95	N.A.	17.17	0.1	15.27	23.87	35.5	1.96
Extractives	Biocompounds agitated solvent extraction	0.2–0.8	N.A.	0.42–1.58	106.52–402.41	543.58	14.31	0.33–1.25	0.16
	Biocompounds supercritical fluid extraction	0.009–0.33	N.A.	54.23–208.87	180.32–681.21	878.3	43.94	0.33–1.25	0.46
All fractions	Biogas	190–750	86.94	33.4–132	0.56	1.12	1.02	1.53	0.75
	Biomethane pressure swing absorption	190–750	86.95	42.5–144.2	2.75	1.24	0.61	1.64	1.3
	Biomethane chemical absorption	190–750	86.94	42.5–144.2	2.98	1.27	0.72	1.83	1.42

The enzymatic hydrolysis of cellulose to obtain glucose was defined as a stage before the bioprocesses presented in Figure 2. Figure 3a,b shows the normalized results for the technical indicators (i.e., mass and energy indicators). The bioprocesses with the best yields were PLA, levulinic acid, lactic acid, ethanol, and ABE production. The carbon conversion efficiency for these processes had a similar behavior. PLA did not present this indicator due to the polymerization process and the increase in molecular weight that took place in the process. The power requirement indicator had low consumption levels for the ABE, lactic acid, ethanol, levulinic acid, and PLA bioprocesses. Regarding thermal energy consumption, the bioprocesses with the lowest consumption were ABE, PLA, levulinic acid, lactic acid, and ethanol. In this sense, the bioprocesses with the best technical behaviors were ABE, levulinic acid, lactic acid, ethanol, and PLA.

Figure 3c presents the normalized economic indicators for the bioprocesses proposed for the cellulose fraction. The bioprocesses with the lowest CapEx were PLA, ABE, lactic acid, levulinic acid, and ethanol. Regarding OpEx, the bioprocesses in ascending order were ABE, PLA, ethanol, levulinic acid, and lactic acid. Finally, the relation between the production cost and the sale price presented better values for the bioprocesses of levulinic acid, ethanol, ABE, lactic acid, and PLA. Based on these indicators, it was determined that the bioprocesses with the highest economic pre-feasibility were ABE, levulinic acid, ethanol, and lactic acid.

Figure 3d shows the climate change related to the bioprocesses for the cellulose fraction. Ethanol, PLA, ABE, levulinic acid, and lactic acid were the bioprocesses, in ascending order, regarding greenhouse gas emissions.

Based on the comprehensive analysis of the technical, economic, and environmental indicators for the cellulose fraction, ABE, PLA, and levulinic acid were the analyzed bioprocesses with the greatest potential to be implemented.

The normalized technical, economic, and environmental indicators for the extractive fraction bioprocesses are presented in Figure 4. The technical indicators in terms of yield and energy consumption (i.e., thermal and electrical) showed that bioactive compounds extraction with stirred solvent presented higher prefeasibility than supercritical fluid extraction (see Figure 4a,c). In economic and environmental terms, parameters such as CapEx, OpEx, and climate change presented the same behaviors described for extracting bioactive compounds with stirred solvents. Therefore, this bioprocess was selected as the best alternative to valorize OKFW.

Finally, the technical, economic, and environmental indicators of the OKFW valorization considering all the fractions (i.e., cellulose, hemicellulose, lignin, starch, pectin, etc.) are presented in Figure 5. For the bioprocesses, the anaerobic digestion was considered as the base for the raw material fractions. For the biomethane production, two purification technologies were considered: pressure swing absorption and chemical adsorption by using amines. Biogas production was the process that presented the best indicators due to its high yield, low capital investment, and environmental impact compared to biomethane production.

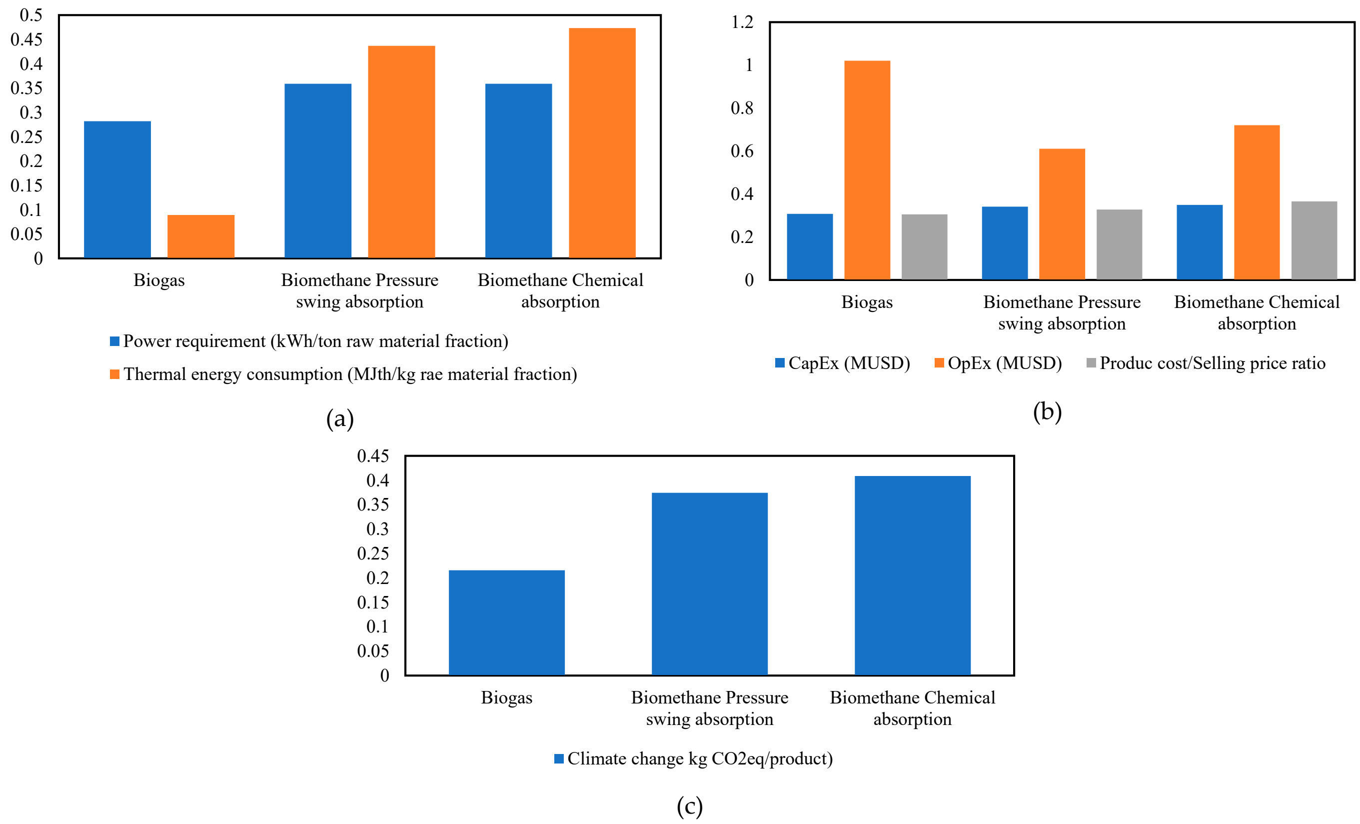

Figure 5. Indicators for the fractions valorization: (**a**) energy indicators; (**b**) economic indicators; and (**c**) environmental indicator [26].

3.1.3. Step 4: Biorefinery Scenarios

The bioprocesses with the best technical, economic, and environmental indicators to be evaluated were ABE, PLA, levulinic acid, stirred solvent extraction, and biogas production. From the conceptual design of the biorefineries, three biorefinery scenarios were generated. The proposed scenarios are presented in Figure 6.

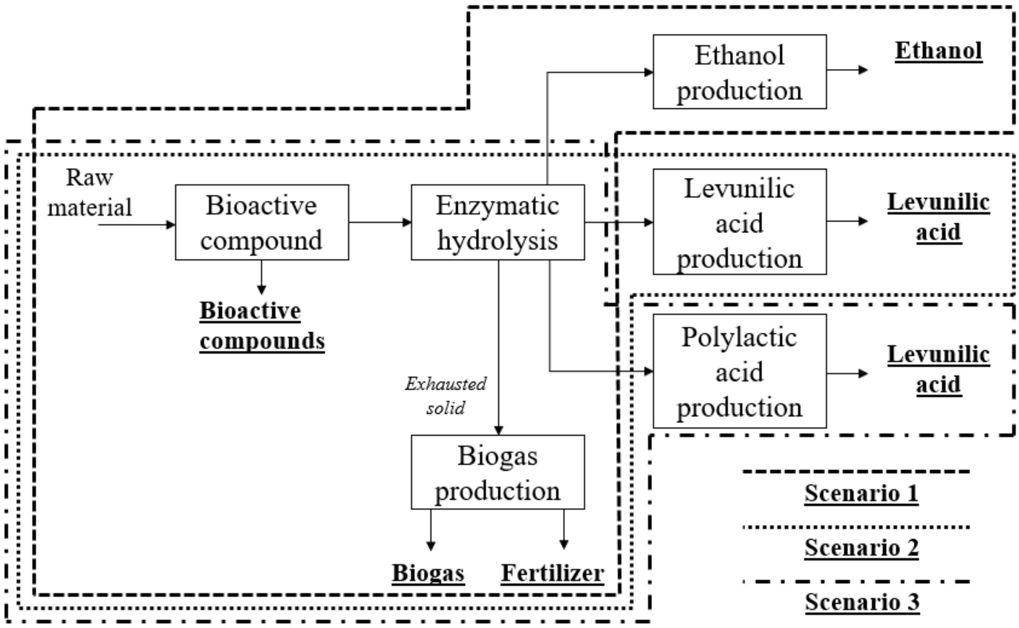

Figure 6. Scenarios for OKFW valorization after incorporating the design strategy for the biorefinery application.

3.1.4. Step 5: Economic Prefeasibility

The levulinic acid production scenario was selected for the economic pre-feasibility analysis. Figure 7 shows the NVP of the levulinic acid production biorefinery for the following three OKFW scales:

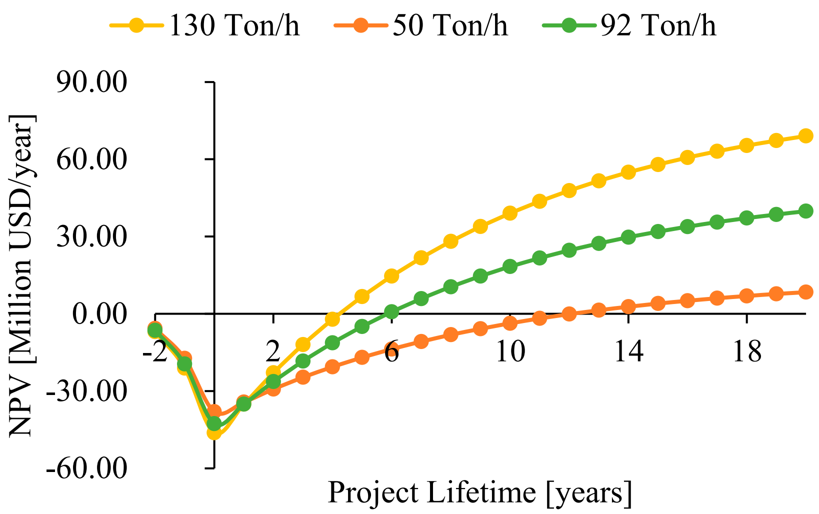

Figure 7. Economic prefeasibility of OKFW valorization.

For all the proposed scales, the biorefinery had viability, and the return periods for investment were located between 4 and 12 years. The CapEx for the biorefinery was between 34 and 48 MUSD. One factor contributing to the biorefinery's economic viability was the high commercial value of levulinic acid compared to other products such as ethanol, butanol, and lactic acid.

3.2. Results for the Other Raw Materials

All the process configurations for the other raw materials are presented in Figure 8. In the case of the small-scale biorefineries (i.e., biorefineries addressed to upgrade FLs), the scenarios introduced low technological complexity processes while the food waste upgrading introduced high technological complexity processes (e.g., levulinic acid). The proposed scenarios for FL and FW valorization are described per zone.

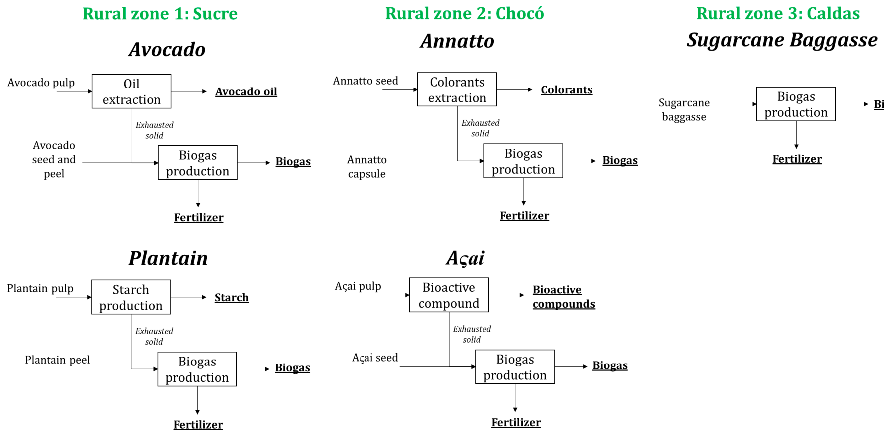

Figure 8. Selected scenarios for food residue biorefineries based on the design strategy.

In Zone 1, rejected avocados are upgraded to produce biogas and avocado oil. The avocado pulp is used to produce avocado oil through cold pressing to guarantee product quality. The process temperature does not exceed 40 °C. The exhausted pulp, peels and seeds are used as raw material to produce biogas. This energy vector is produced by using sludge as inoculum from the local wastewater treatment plant. Rejected plantain is converted into starch and biogas. Plantain pulp is used as a raw material in the starch production line. Additives such as citric acid and sodium hydroxide are used to extract the starch. Biogas is produced using plantain peels as a raw material since this fraction has a considerable biogas production yield. The products obtained by implementing the proposed biorefinery configuration can be commercialized at the local level.

For Zone 2 (Choco), annatto seeds are used as a raw material. First, colorants are extracted by using a green solvent such as ethanol. Afterward, the exhausted solids are used to produce biogas as an energy vector and possible source of electricity. Instead, acai pulp is also used to extract bioactive compounds by using green solvents. The exhausted pulp is co-digested with acai seeds to produce biogas. Finally, in Zone 3 (Samana), sugarcane bagasse is upgraded to produce biogas which can be used to improve the thermal efficiency of the brown-sugar production. Regarding the OKFW, first, the fat content is extracted by using a pressing machine. Then, the solid is used to extract bioactive compounds by using green solvents. Afterward, the extracted solid is subjected to an enzymatic hydrolysis process to produce fermentable sugars as platforms for obtaining added-value products. The liquor of the saccharification process is used to produce levulinic acid when implementing the Biofine process. The exhausted solid after enzymatic hydrolysis is used to produce biogas as thermal energy source and power.

The economic assessment of the proposed biorefineries to upgrade FL and FW is presented in Figure 9. The economic analysis demonstrated the potential of using rejected avocado in Zone 1, acai and annatto as raw materials in Zone 2, and OKFW in Zone 3. Rejected avocado was more feasible than plantain since the avocado oil production process has a lower capital investment than the starch processing line. Moreover, starch has a lower commercial value (USD 0.83 per kg) than avocado oil (USD 8.15 per kg). Then, the economic feasibility of the proposed scenarios was determined by the selected products for upgrading. Annatto and acai are potential raw materials for producing colorants and bioactive compounds. Both products have a high market cost since the food, cosmetic, and pharmaceutical sectors have well-defined uses.

The processing scale was not an issue since a low processing scale has a good economic performance. Sugarcane bagasse used only as a biogas source is not feasible at the economic level since biogas has a low commercial value. Even if the biogas is converted to energy (electricity), the process is unfeasible since Samana has hydro-energy as a renewable energy source. Therefore, biogas production should be considered as a complement for other process.

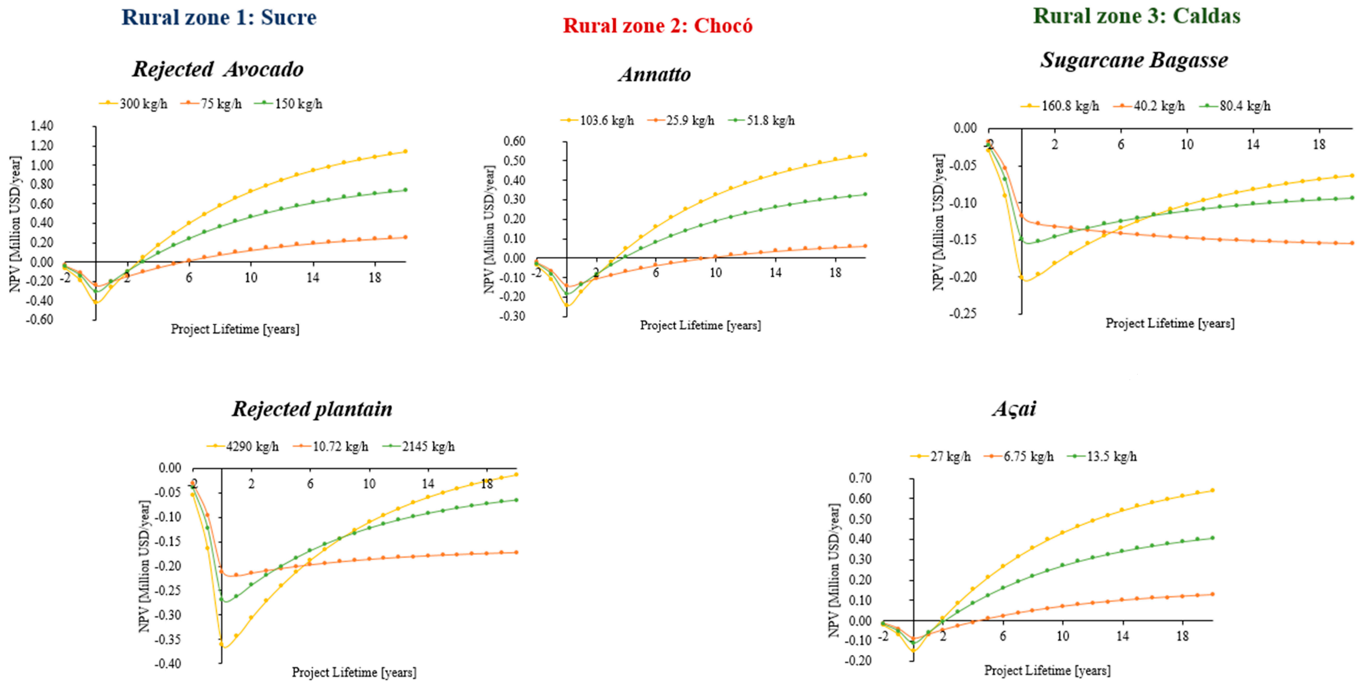

Figure 9. Economic prefeasibility of the food residue biorefineries.

3.3. Sustainability Analysis

The sustainability analysis of the proposed biorefineries for upgrading FLs and FWs must involve the triple bottom line (i.e., economic, environmental, and social benefits). The economic and environmental performances of the biorefineries were ensured by the bioprocess screening conducted in the previous steps. Then, social aspects must be involved to understand the complete impacts of the biorefineries. Indicators related to job creation and access to material resources should be included. Despite the numbers of these indicators, the implementation of new processes addressed to upgrade FLs and FWs can promote the development of more sustainable communities at the local and regional levels. In addition, the sustainability analysis of the proposed biorefineries ensures the possibility of implementing these processes in real life. The results obtained for each zone reflect the potential of the development of bio-based products for boosting rural bioeconomies.

In the rural zones of Sucre, the rejected avocado valorization presented a better economic feasibility than upgrading the rejected plantain. The same behavior was found for the environmental perspective due to the low carbon dioxide emissions of rejected avocado being upgraded to avocado oil and biogas. In the rural zones of Choco, the acai and annatto valorization were feasible from the economic perspective due to the production and commercialization of added-value products (i.e., colorants and bioactive compounds). The acai valorization presented the best economic performance because of the high selling price of its bioactive compounds. From the environmental perspective, both scenarios in Choco presented similar environmental impacts.

Finally, in the rural zones of Caldas, the sugarcane bagasse valorization was not feasible for producing biogas. Moreover, the OKFW had a good economic performance. Nevertheless, the technological context for the biorefinery implementation could not be a rural zone. This scenario was presented as a future alternative to be implemented in more developed regions with better logistics and technological development. This study demonstrated the possible development of a rural bioeconomy under the biorefinery concept.

3.4. Entrepreneurship Alternatives in Rural Zones

The results obtained for the FL and FW valuation scenarios can make it possible to define sustainability before generating ventures. In addition, technical and environmental indicators can be differential factors that promote the positioning of products through seals that denote the extensive use of resources. For example, calculations of air emissions generated determine the carbon footprint of products that can be used on a label to increase marketing potential. The valuation schemes proposed for the FLs and FWs generated in the three areas analyzed in this paper serve as a fundamental basis for the development of enterprises. Furthermore, this perspective defines the viability of the schemes considering limiting factors such as waste generation flows, socio-economic contexts, technological contexts, and bioprocess TRLs. Based on these results, the probability of success in formulating projects and creating ventures can be increased.

The upgrading alternatives for the agricultural products proposed in this research paper can be applied to other agricultural products obtained in other rural regions of Colombia. For instance, new alternatives for valorizing cocoa residues can be proposed based on cocoa's high production rate in South Colombia (e.g., in Nariño and Putumayo). These alternatives can involve biorefineries addressed to produce cellulose fibers, food additives, and bioenergy. On the other hand, the methodology applied for upgrading agricultural products and residues can be extrapolated to other crops such as cassava, corn, palm oil, rice, mango, and coffee. Thus, the methodology and results reported in this research paper can be considered as the basis for boosting new alternatives for sustainably upgrading biomasses.

4. Conclusions

The sustainability analysis of a biorefinery is delimited through the selection of a bioprocess portfolio based on the food residues' chemical compositions (fractions). For the case studies, technical and economic prefeasibility was demonstrated using the bioprocess portfolio. For the OKFW, the filtration processes of the biorefinery strategy resulted in the scenarios with the greatest potential for evaluation being the production of levulinic acid, PLA, and ABE from the cellulose fraction. In addition, the production of biogas was determined to be the best process for the integral use of the raw material considering the exhausted solid generated after the extraction process and enzymatic hydrolysis. On the other hand, the design strategy allowed for the identification of biorefinery schemes for the valorization of the FLs generated in rural areas (i.e., Caldas, Chocó, and Sucre) with commercialization potential at the local level. The foregoing highlights the role of conceptual design in the proposition of ventures in different areas and contexts. Finally, the implantation of the design strategy for food waste biorefineries allowed for elucidating the best scenarios to be implemented as entrepreneurship initiatives in rural zones in Colombia.

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