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Apple Pomace Integrated Biorefinery for Biofuels Production: A Techno-Economic and Environmental Sustainability Analysis

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Abstract: The combination of techno-economic process modelling and life cycle assessment is an integrated methodology that addresses quantitative operational data, and evaluates the emissions associated with any process under development. In particular, the valorisation of waste streams within the context of the circular economy could be considered a valid and promising approach, especially regarding techno-economic and environmental indicators. This manuscript aims to evaluate the integral valorisation of apple pomace from the processing industry into bioethanol, and vinasses (a byproduct of the distillation process) into biogas and digestate as biofertiliser. In addition to biogas production, lagooning and composting were considered as strategies for vinasse management. After the conceptual design of the process options was completed, the environmental profile of bioethanol production was estimated across different scenarios. When biogas production was integrated to reduce the biorefinery's energy demand, the carbon footprint was 1.13 kg CO_2eq·kg^{-1}. This footprint increased to values around four when lagooning and composting were used as vinasse management strategies. Although the economic dimension posed a significant limitation due to high investment costs, the eco-efficiency analysis showed that the scenario of the co-production of bioethanol and biogas is the best alternative. Despite the promising results, further research is needed to explore the recovery of additional co-products to develop a high-potential strategy for apple pomace.

Keywords: life cycle assessment; circular bioeconomy; bioethanol; biogas; bioenergy; vinasse

1. Introduction

Increased demand for food and energy in a fossil fuel-based economy has led to one of the greatest challenges to society, namely the climate change crisis. Despite initiatives aimed at reducing global fossil fuel consumption, the inevitable consequence of population growth is an increase in demand from 89 to 115 million barrels per day during the period from 2013–2040, posing a risk of fossil fuel depletion within an undetermined timeframe [1]. Additionally, the current linear economy model has resulted in organic waste becoming a major fraction of the total global waste volume [2]. To address these challenges, the biorefinery concept has emerged to valorise waste biomass into a wide range of high-value-added products such as biofuels, bioactive compounds, proteins, biopolymers, and organic acids, among others [3]. Biofuels, mainly biodiesel and bioethanol, are renewable sources of primary energy that play a key role in mitigating both energy insecurity and the climate crisis, as they can be used as fuel additives or in their pure form [4].

Bioethanol is widely used as a solvent, fuel, and feedstock to produce compounds with various industrial applications [5]. It can be produced from the fermentation of agricultural crops and forest sources, referred to as first-generation (1G) sources, such as corn [6], wheat and cassava [7], sugar beet [8], and forest biomass [9,10], among others. However, the use of agricultural resources impacts ecosystems like grasslands, forests, pastures, and protected areas, and often involves intensive management practices, such as the use of synthetic fertilisers. The increasing demand for bioenergy has led to socioeconomic effects, including rising food prices, fodder shortages, and increasing competition for land [11]. Moreover, replacing 1G with second-generation (2G) bioethanol could free up 1.2 million hectares for food production (more than 5% of wheat land in the EU) or for efforts to mitigate biodiversity loss [8].

The 2G bioethanol route has gained attention as a way to address the aforementioned issues. The 2G routes can be based on various sources such as corn stover [12], wheat straw [13], sweet sorghum stalk [14], banana peel [3], and food waste [15], among others. One of the most significant suppliers of these types of raw materials is the food industry, which has a large environmental impact when not properly managed [16]. In the food industry, apples are one of the most widely consumed fresh fruits worldwide due to their flavour and high nutritional value [17]. Besides fresh consumption, apples play an important role in the food industry, particularly in the production of concentrated juices and dehydrated products [2]. Apple pomace, a by-product generated from apple processing industry, requires proper treatment to prevent environmental contamination [18]. A literature review performed by Awasthi et al. [16] revealed the scarcity of research on the use of apple pomace for producing bioproducts such as bioethanol, butanol, 2,3-butanediol, and organic acids, as well as the lack of knowledge regarding process scale-up and the technoeconomic and environmental implications of these potential biorefinery platforms.

Chile is the leading exporter of apples in the southern hemisphere and ranks fourth worldwide (after China, USA, and Italy), accounting 9.5% of global exports [19]. Traditionally, in this country, apple pomace has been left on agricultural land or used as animal feed. Hernández et al. [20] conducted a laboratory-scale study on the feasibility of producing 2G bioethanol from apple pomace, using only the liquid fraction obtained after pressing the biomass, and without enzymatic hydrolysis to reduce cost and minimize the environmental impacts associated with enzyme use [21]. The study also analysed the characterisation of vinasse, a by-product. To assess the economic and environmental feasibility of bio-based valorisation pathways, techno-economic analysis (TEA) and life cycle assessment (LCA) are widely used methodologies [22]. TEA evaluates the technical and economic feasibility of a technology by combining mass and energy balances with an economic evaluation based on capital, operating and production costs [23]. LCA, on the other hand, assesses the environmental impacts of products and services throughout their life cycle [24]. The combination of both approaches offers a comprehensive view of biorefinery platforms, helping to identify key opportunities for implementation and improvement, to avoid critical environmental and economic challenges at the early design phase.

This manuscript provides a first attempt to valorise apple pomace using a cascade biorefinery approach for the co-production of bioethanol and biogas. This manuscript aims to demonstrate the environmental and economic feasibility of the simulated facility. Specifically, this work has the following four main objectives: (i) to model the industrial-scale process of 2G bioethanol production using apple pomace from the processing industry; (ii) to conduct a techno-economic analysis based on process design data; (iii) to evaluate the environmental burdens of producing ethanol using apple pomace from a life cycle perspective; and (iv) to assess the eco-efficiency performance of co-producing bioethanol and biogas in comparison to two traditional vinasse treatment strategies, namely composting and lagooning.

2. Materials and Methods

2.1. Biorefinery Modelling

The modelling of the 2G bioethanol production process from apple pomace (vaGranny Smith, Fuji, Pink Lady, Red Delicious, Gala, from Maule region, Chile) was based on the work performed by Hernández et al. [20]. The biorefinery plant design has an annual processing capacity of 4000 tons of apple pomace, operating 330 days per year. This capacity level was selected as it corresponds to the annual pomace production of one of the main apple processing plants in Chile (34.9583° S, 71.1256° W), where the platform is assumed to be integrated. The biorefinery design consists of the following five main stages: pre-treatment, fermentation, purification, steam generation from solid residual biomass, and vinasse treatment (see Figure 1). The process was modelled using Superpro designer® software v11 [25].

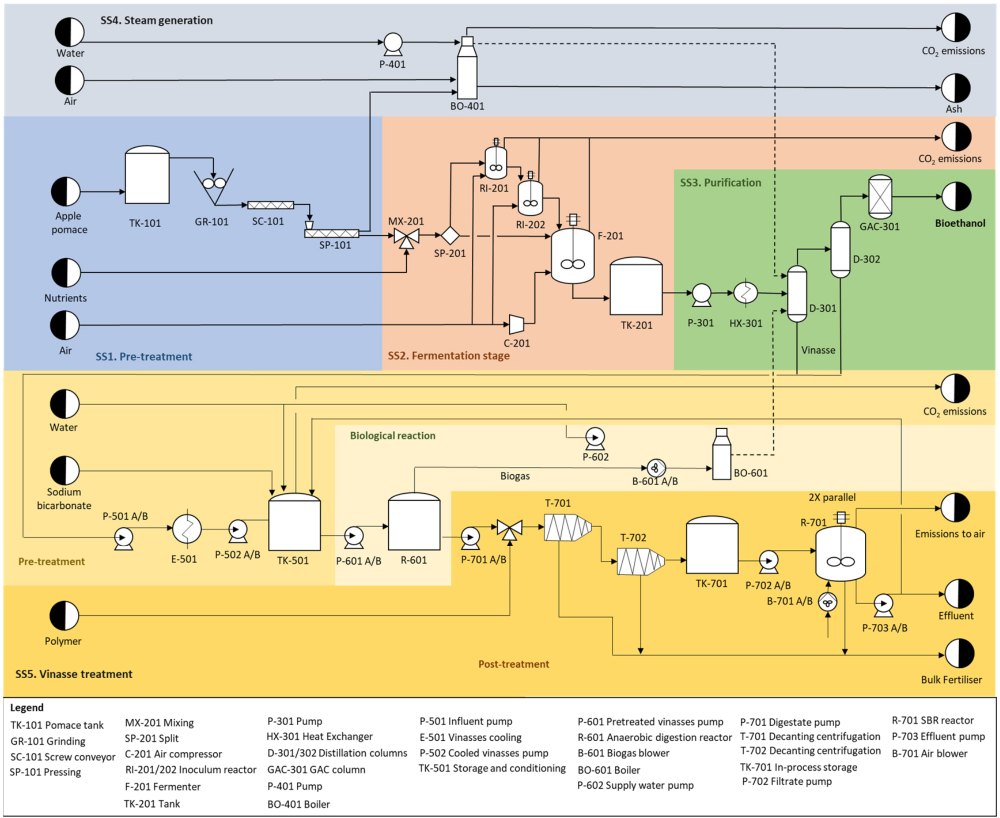

Figure 1. Flow diagram of apple pomace 2G bioethanol with vinasse treatment for the biogas production.

In the pre-treatment stage, the residual pomace is milled to obtain a homogenised flow and pressed to extract the free liquid phase, which represents approximately 59% (v/v) and is sent to the fermentation section. The solid phase is sent to a steam generation boiler to reduce the energy demand of the plant. In the fermentation stage, it was assumed that 5% of the fermentable sugars are used for inoculum preparation (i.e., yeast production). Nutrients were added at a concentration of 0.4 $g{\cdot}L^{-1}$, and the fermentation process lasts 144 h at 30 °C [20].

The broth obtained from the fermenters was subsequently fed into a storage tank (TK-201). In the purification stage, distillation columns were used to recover and purify the ethanol stream. The first column (D-101) produces a 43% ethanol solution in the distillate, while the second column (D-102) generates an ethanol solution of approximately 92%. The distillation column bottoms (i.e., vinasse) are treated to produce biogas, which is burned in a boiler for steam production. After distillation, ethanol dehydration is performed in an activated carbon column to produce fuel-grade ethanol containing less than 0.1% water.

The treatment of apple vinasse involves an anaerobic digestion (AD) process, modelled based on the work of Estévez et al. [26] and the vinasse characterisation provided by Hernández et al. [20]. After the AD reactor, a solid–liquid separation is performed using a decanter centrifuge to obtain filtrate and cake streams. The filtrate is treated aerobically at 35 °C and pH 7 in a sequential batch reactor (SBR) to meet the discharge standards for treated effluents (according to European Council Directive 91/271/EEC). The cake, along with the sludge from the SBR process, could be used as a biofertiliser.

Comparison with Other Vinasse Treatment Alternatives

Biogas production from the valorisation of vinasse through AD was the base scenario (E + B) of the 2G bioethanol biorefinery design. However, there are other conventional alternatives for treating this undesirable by-product. To compare the results from the baseline scenario, from both environmental and economic perspectives, lagooning (E + L) and composting (E + C) were considered. The former was modelled based on the study of Barrera et al. [27] and the latter was analysed following the work of Estévez et al. [26].

- Scenario E + L: The vinasse is sent to lagoons with a concentration of chemical oxygen demand (COD) of around 40 g·L^{-1} at 35 °C. The removal efficiency of biodegradable COD in lagoons was assumed to be 99% [27]. In this scenario, methane and carbon dioxide are emitted directly into the atmosphere, while the liquid effluent is pumped for fertigation of agricultural or green areas. Additionally, sludge is produced for use as a bulk biological fertiliser. For this purpose, two pumps were considered with a flow capacity of 122 m^3·h^{-1}. The land required for this treatment was estimated at 7.8 ha. The process design is shown in Figure 2.

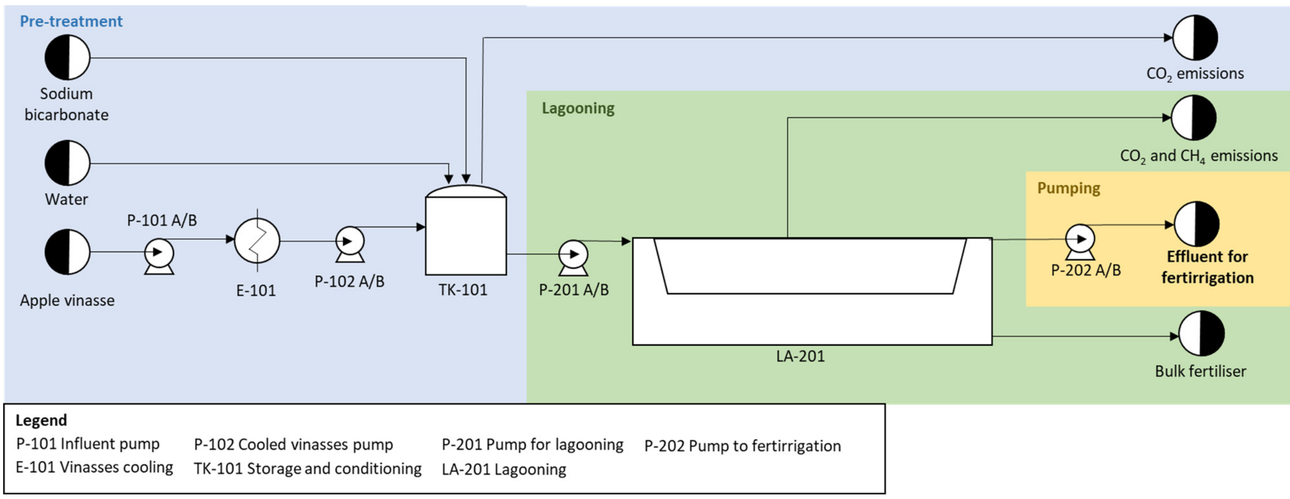

Figure 2. Flow diagram of lagooning alternative for vinasse treatment.

- Scenario E + C: It was designed as an individual forced aerated windrow with a total solid concentration of 40%. The volume of the pile was estimated considering the vinasse flow rate for continuous operation and the residence time required to complete the aerobic degradation of organic matter. The land required for this activity was estimated at 4.8 ha.

2.2. *Techno-Economic Analysis*

2.2.1. Estimation of Total Capital Investment

Mass and energy balances, along with equipment sizes, were estimated using Superpro designer® v11 process design software, while free-on-board purchased equipment costs (Ceq.fob) were estimated based on textbooks and reports [28–30]. The Fixed Capital Investment (FCI) was calculated by multiplying the sum of the Ceq.fob with a Lang factor of 5 [31], chosen due to the need to construct a biorefinery plant with new, high-risk technology and costly construction materials for the process equipment [32]. Working capital (WC) was assumed to be 5% of the FCI value as recommended by Davis et al. [33]. Finally, the total capital investment was obtained by summing the FCI and WC values.

2.2.2. Estimation of Manufacturing Costs

The manufacturing cost (COM) was estimated using the Equation (1) proposed by Turton et al. [30]:

$$COM = 0.18 \times FCI + 2.73 \times C_{OL} + 1.23 \times (C_{UT} + C_{RM} + C_{WT}) \quad (1)$$

where C_{OL} represents the operating labour cost. C_{UT} corresponds to utility expenses and C_{RM} represents raw material expenses. Based on Turton et al. [30], these coefficients account for the contribution of all secondary product cost categories, such as maintenance, marketing, and research and development.

For labour cost (C_{OL}), the methodology reported by Ulrich and Vasudevan [34] was used, considering the total quantity of workers required based on the annual operation (see Table S1 in the Supplementary Materials), each worker's hours, and the average labour cost. Utility costs (C_{UT}) were estimated by multiplying the unit cost by the amount required by each utility item. More information about unitary costs is provided in Table S2 in the Supplementary Materials. Similarly, the costs associated with raw materials (C_{RM}) and waste treatment (C_{WT}) were estimated based on the unitary cost and the demanded amount (see Tables S3 and S4 in the Supplementary Materials).

2.2.3. Costs Externalities

Environmental prices are external costs that represent welfare loss due to pollutant emissions and are expressed as an economic accounting parameter per unit impact [35]. Since the charges are monetised in euros (€), they were converted to dollars at an exchange rate of 1.18 [36]. The purpose of considering cost externalities is to assess their impact on the economic feasibility of designing a bio-based business model that aligns with corporate social responsibility, as well as to enable a comparative evaluation of the scenarios analysed for 2G bioethanol production and the effectiveness of selected vinasse management strategies.

2.2.4. Economic Analysis and TEA Indicators

To determine the economic viability of the valorisation route through TEA indicators (e.g., NPV, MSP), a discounted cash flow (DCF) analysis was carried out [37]. For this purpose, the parameters reported by Davis et al. [33] were used, as shown in Table 1. For the calculation of asset depreciation, seven years were assumed based on the Modified Accelerated Cost Recovery System (MARS). The MSP per kg product was estimated by determining the market price of the product at which the Net Present Value (NPV) reaches zero at the end of plant lifetime. TEA indicators used for the profitability assessment were MSP, NPV, Optimum Plant Capacity (OPC) leading to minimum COM, the Minimum Feedstock Requirements (MFR) that represents the amount of feedstock required to satisfy the OPC, and the Discounted Payback Period (DPP). OPC denotes the capacity level where COM or MSP values reach a plateau and thereafter remain constant. For this analysis, bioethanol production scales were evaluated from 217 $t \cdot y^{-1}$ (i.e., the capacity of the processing plant) to 43 $kt \cdot y^{-1}$. DPP is the time required, after start-up, to recover the fixed capital investment (FCI) with all cash flows discounted to time zero [30]. Furthermore, it was assumed that sludge fertiliser from anaerobic digestion could be sold at 0.58 and 0.87 $€ \cdot kg^{-1}$ of nitrogen and phosphorus content, respectively [38]. For the two additional scenarios evaluated for vinasse treatment integrated with the 2G bioethanol biorefinery (i.e., E + C and E + L), the techno-economic analysis was performed at the optimum plant capacity identified for the baseline scenario.

Table 1. Parameters of the DCF analysis [33].

DCF Parameters	Value
Discount rate	10%
Plant lifetime	30 years
Equity financing	100%
Corporate tax rate	35%
Plant construction duration	3 years
Percentage of project cost in the 1st, 2nd, and 3rd year of construction	8–60–32%
Salvage value	0
Land costs	0

2.3. Life Cycle Assessment

The environmental assessment from a life cycle perspective was conducted following ISO 14040–14044 guidelines [24,39], which outline the four steps of this methodology: aim and scope, life cycle inventory, impact assessment, and interpretation.

2.3.1. Aim and Scope of the Study

The aim of this research is to estimate the potential environmental burdens of 2G bioethanol production from apple pomace obtained in the processing industry under a biorefinery concept. To this end, a cradle-to-biorefinery-gate approach (see Figure 3) was adopted, covering activities from feedstock extraction, apple cultivation and processing, to bioethanol production and by-product (i.e., vinasse) treatment in the biorefinery plant. For the functional unit (FU), environmental loads were expressed in terms of mass (1 kg), volume (1 L, based on density of 789 kg·m^3), and energy (1 MJ, based on heating value of 23.21 MJ·kg^{-1}) to allow comparison with results from other studies in the literature.

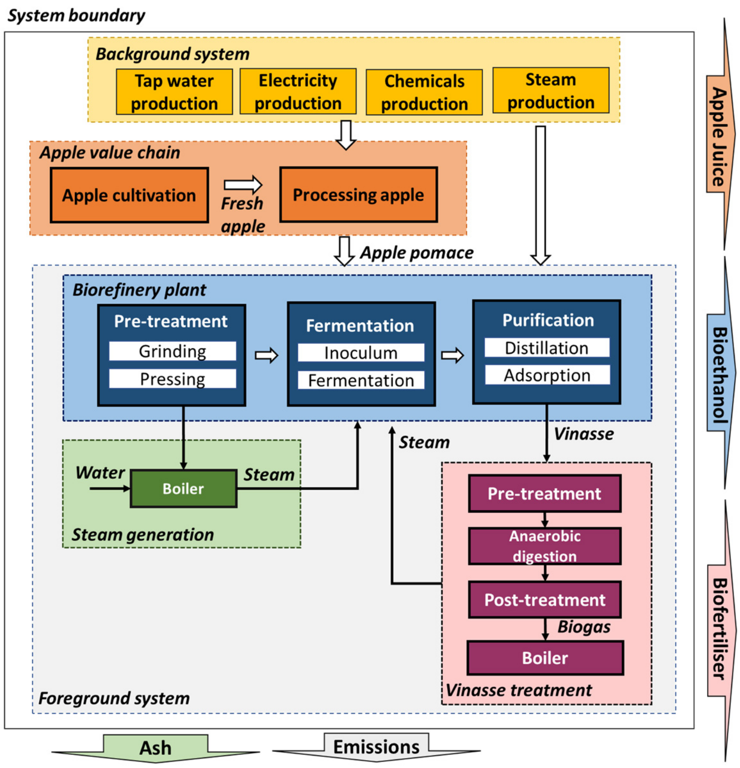

Figure 3. System boundary of the 2G apple bioethanol biorefinery.

2.3.2. Life Cycle Inventory

The life cycle inventory (LCI), which considers the mass and energy balances of the biorefinery platform, is presented in Table S5 in the Supplementary Materials. Electricity production was modelled considering the energy profile of Chile in 2021, with the energy mix comprising 33% coal, 14% solar, 13% hydraulic, 12% natural gas, and 9% wind, among others [40]. Furthermore, external steam supply was assumed to come from cogeneration systems to avoid fossil fuel consumption. Background processes were taken from the Ecoinvent® v3.8 database [41], accounting for the apple cultivation stage. Environmental loads of juice concentrate production were taken from the research conducted by Cheng et al. [42]. Both the apple orchards and processing plant are located in the same region (Maule) in the Central Valley of Chile (34.9583° S, 71.1256° W). Thus, the transport of fresh apples to the processing plant and of apple pomace to the biorefinery was omitted, assuming that the biorefinery plant would be adjacent to the processing plant.

The economic allocation method was used to distribute environmental loads between the apple juice product and apple pomace in the processing stage. Market prices of 2.3 $\$\cdot kg^{-1}$ for concentrated apple juice [43] and 0.01 $\$\cdot kg^{-1}$ for apple pomace were used, the latter according to the information provided by the processing plant. The annual production yields for apple juice and pomace were 2.9 kt and 4.0 kt, respectively, resulting in allocation factors of 99.7% and 0.3% for each, respectively. Furthermore, although the vinasse treatment section produces a bio-fertiliser from the AD process, all the burdens were allocated to the main product (i.e., bioethanol). Finally, LCI data were converted into environmental impacts using SimaPro® v9.4.0.2 software [44]. Inventory data for lagooning and composting treatment of vinasse are provided in Tables S6 and S7 in the Supplementary Materials, respectively.

2.3.3. Life Cycle Impact Assessment (LCIA)

To estimate the potential environmental burdens of 2G bioethanol, characterisation factors from the 18 midpoints categories of the ReCiPe 2016 (H) V1.07/World (2010) (H) method [45] were considered. This method was selected as it provides characterisation factors on a global scale. Additionally, cumulative energy demand (Low Heating Values) v1 [46] was used, since it represents one of the most appropriate LCIA methodologies for energy requirements [47].

2.4. Eco-Efficiency Assessment

To compare the economic and environmental feasibility of 2G bioethanol production coupled with biogas production against two traditional vinasse treatments, an eco-efficiency analysis was conducted. Eco-efficiency is a management tool that relates the environmental impacts of a product system to its economic performance [48], thus promoting life-cycle sustainability thinking through the identification of alternative options [49]. Since various monetary indicators can represent economic performance within the eco-efficiency concept, cost and benefits monetary indicators were used here. For each bioethanol scenario evaluated, the eco-efficiency indicator ($ECOF_{ij}$) was defined as the ratio between the manufacturing cost of scenario i and the environmental burden related to impact category j, as presented in Equation (2):

$$ECOF_{ij} = \frac{COM_i}{EI_{ij}} \tag{2}$$

where COM_i is the manufacturing cost obtained using Equation (1) presented in Section 2.2.2, and EI_{ij} refers to the environmental impacts of scenario i for category j. Secondly, $ECOF_{ij}$ with the benefits approach is presented in Equation (3):

$$ECOF_{ij} = \frac{IN_i - COM_i}{EI_{ij}} \tag{3}$$

where IN_i represents the estimated revenue for each bioethanol scenario i. For both, the higher the $ECOF$ score, the more eco-efficient a scenario is.

3. Results and Discussion

3.1. Tecno-Economic Results

3.1.1. Fixed Capital Investment and Manufacturing Cost

As mentioned in Section 2.2.4, different production scales were analysed to identify the production level at which the FCI per kg of bioethanol reaches a constant value. Figure 4 shows the results obtained for the FCI, MSP and COM indicators. The results clearly show that a plateau is reached at a processing capacity of about 21 kt·y^{-1}. The FCI values range from MM$5 to MM$500 per year of production, decreasing from 22 to 12 $·kg^{-1} as plant capacity increases. Furthermore, the COM indicators for the biorefinery at different production scales range from 32 to about 4 $·kg^{-1}.

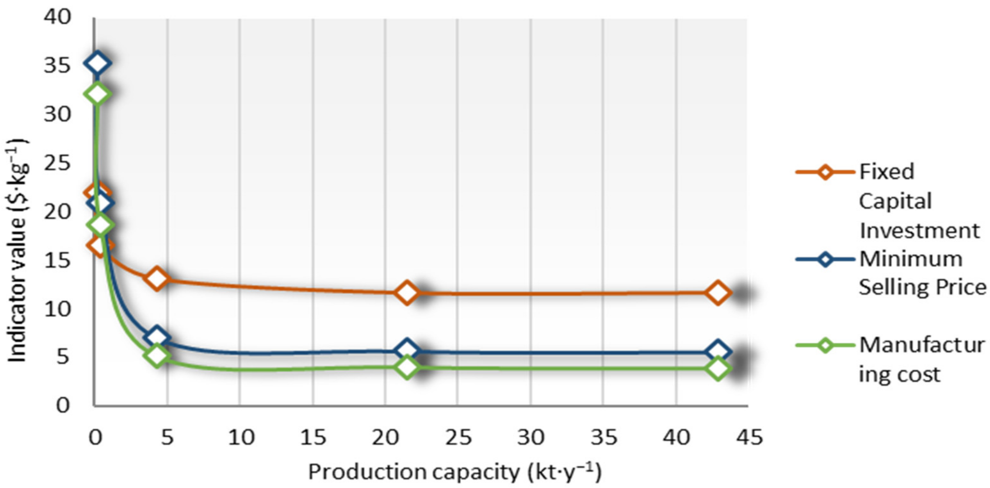

Figure 4. Techno-economic indicators at different scale of production.

3.1.2. Minimum Selling Price

The MSP for bioethanol at various plant capacities is presented in Figure 4. The values range from 35.3 $·kg^{-1} at the lowest capacity scale to about 5.7 $·kg^{-1} where the MSP indicator reaches a plateau. Based on the current production capacity of the apple processing plant (4 kt of apple pomace), the MSP value of bioethanol obtained is too high to introduce the product to the market, as it reaches the maximum MSP (i.e., 35.3 $·kg^{-1}).

3.1.3. TEA Indicators at the Optimum Plant Capacity

The estimated equipment size, purchase equipment cost and FCI at the OPC level for bioethanol production are presented in Table 2. The FCI indicator shows a value of $MM 250, with the vinasse valorisation stage (i.e., biogas production), contributing the most at about 73% of the total FCI, followed by the fermentation section at around 18%. The MSP indicator was 5.7 $·kg^{-1} of bioethanol, while the NPV, assuming a 10% discount rate for the selling price, was close to MM$77. The COM indicator per kg of bioethanol was $4.0. The payback period for the biorefinery plant at OPC ranges from 25 to 7 years, with the profit rate varying from 1% to 25% with respect to the MSP value (see Figure 5). In addition, the MFR indicator at OPC level corresponds to 396 kt·y^{-1} of apple pomace. This metric could be useful for evaluating the feasibility of constructing an apple pomace biorefinery in Chile, depending on the availability of feedstock in the country. Since the current capacity level is not economically viable, further research is needed to determine an optimal biorefinery location and secure feedstock supply from multiple suppliers.

Table 2. Purchase cost of the most important units to produce 21.4 kt·y^{-1} bioethanol (OPC).

Section	Equipment	Value	Unit	Ceq.fob ($)	Amount	Total ($)
Pre-treatment	Storage tank [1]	54.7	m^3	$109,438	1	$109,438
	Grinder [2]	50.0	t/h	$40,000	1	$40,000
	Screw conveyor [1]	21.3	m^2	$20,400	2	$40,801
	Screw Pressing [2]	50.0	t/h	$120,000	14	$1,680,000
Fermentation	Seed reactor [1]	27.2	m^3	$73,668	3	$221,003
	Seed reactor [3]	407.9	m^3	$384,188	1	$384,188
	Fermenter [3]	711.1	m^3	$673,465	12	$8,081,581
	Centrifugal compressor [1]	226.4	kW	$235,996	1	$235,996
	Storage tank [1]	309.4	m^3	$57,243	1	$57,243
Purification	Pump [1]	1.4	kW	$8245	1	$8245
	Heat exchanger [1]	72.3	m^2	$90,158	2	$180,315
	Heat exchanger [1]	2.2	m^2	$9821	1	$9821
	Centrifugal compressor [1]	18.0	kW	$11,918	1	$11,918
	GAC Adsorber [1]	308.9	m^3	$190,516	11	$2,095,679
	Distillation column [1]	14.0	m^3	$57,106	2	$114,211
	Distillation column [1]	23.6	m^3	$42,806	1	$42,806
Steam generation	Boiler plant [2]	1.217	t/h	$31,000	1	$31,000
Vinasse treatment (for biogas production)	Pumps [1]	2.7	kW	$35,277	16	$94,404
	Heat exchanger [1]	247	m^2	$34,303	1	$34,303
	Storage tank [1]	43.3	m^3	$33,012	1	$33,012
	Reactor AD [3]	6000	m^3	$1,337,904	22	$29,433,887
	Centrifuges [2]	300	kW	$340,000	4	$680,000
	Storage tank [1]	30.6	m^3	$25,179	1	$25,179
	Reactor [3]	757	m^3	$589,957	9	$5,309,611
	Blower biogas [2]	0.5	m^3/s	$24,000	22	$528,000
	Blower aeration [2]	0.4	m^3/s	$24,000	9	$216,000
	Mixer [1]	3.8	kW	$17,987	9	$161,883
	Boiler plant [2]	17.7	t/h	$223,200	1	$223,200

[1] [30], [2] [29], [3] [28].

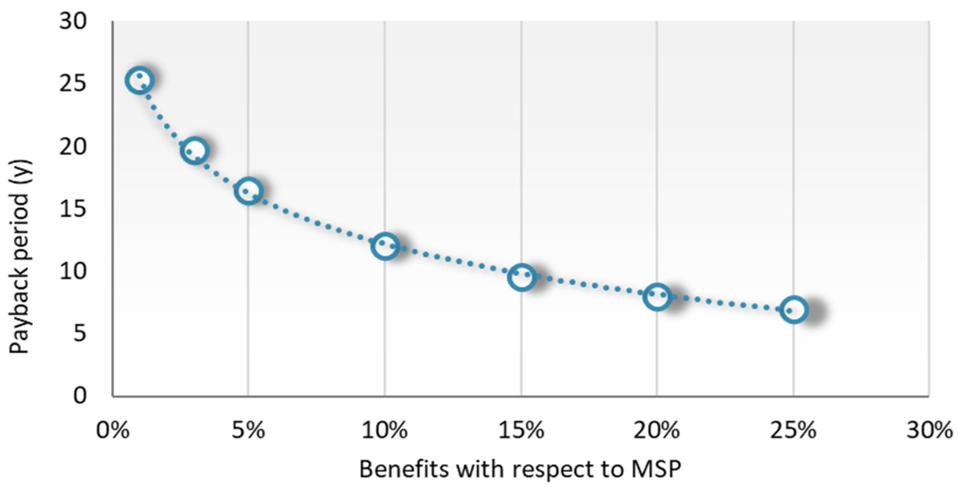

Figure 5. Payback period values of the biorefinery at different benefit levels.

3.1.4. Comparison of TEA Results with the Literature

Due to the limited publications on the design and operation of apple pomace facilities for bioenergy production, the comparative techno-economic evaluation of this study's results is restricted. For this reason, the comparison focuses on the outcomes of other feedstocks.

Based on the review performed by Jarunglumlert and Prommuak [50], the MSP of bioethanol ranges from 0.34–1.8 $·L^{-1} with the variability attributed to different issues, such as the selected feedstock, pre-treatment method, and co-products processing. For example, Joelsson et al. [51] assessed biogas and ethanol production from wheat straw, assuming biogas would be sold and converted to vehicle fuel. They found an ethanol MSP of 0.72–0.87 €·L^{-1}, which decreased to 0.46–0.60 €·L^{-1} when the biogas was upgraded to vehicle fuel. In this regard, if both bioethanol and biogas are sold from the apple-based biorefinery, the MSP of bioethanol could reach 5.5 and 5.4 $·kg^{-1}, assuming biogas prices of 33 and 67 €·MWh^{-1} [51], respectively. Furthermore, if public financing were provided for vinasse treatment, the MSP of bioethanol could decrease (from the 5.5 $·kg^{-1}) to 2.6 $·kg^{-1}, which is still above literature and market values.

The economic unfeasibility of this system could align with the findings of Demichelis et al. [52], who identified that the type of feedstock significantly affects the economic performance of biorefineries. In this manuscript, the carbohydrate content (on a dry basis) of the apple pomace studied was about 10%, with a soluble sugar content of about 6–8% [20]. In this regard, Demichelis et al. [52] identified that using sugar-based feedstock (e.g., sugar cane) was more cost-effective than starch-based feedstock (e.g., rice straw), with carbon content exceeding 45–50 wt%. Therefore, one of the main economic limitations of using apple pomace as feedstock is its relatively low sugar content. Further studies could focus on the co-production of other valuable bioproducts from apple pomace to achieve a more cost-effective system.

3.1.5. Comparison of Scenarios for Vinasse Treatment

Table 3 presents the findings of FCI for traditional vinasse treatment in the E + C and E + L scenarios at the OPC level. The FCI indicator for the E + C scenario was about MM$75, with vinasse treatment representing about of 11% of the total FCI. In contrast, the E + L scenario showed an FCI of $67 million, approximately 12% lower than E + C, with vinasse treatment contributing only 1% of the total. Comparing the FCI for vinasse valorisation across the three scenarios, biogas production scenario showed an FCI value of MM$183, whereas lagooning and composting reached about $388,503 and MM$8, respectively.

Table 3. Characteristic size and purchase equipment cost of the unit operations of vinasse treatment at OPC.

Section	Equipment	Parameter	Unit	Ceq.fob ($)	Amount	Total ($)
Lagooning	Pumps [1]	0.7	kW	20,034	4	20,034
	Heat exchanger [1]	129.0	m^2	25,890	1	25,890
	Storage tank [1]	41.2	m^3	31,776	1	31,776
Composting	Pumps [1]	0.9	kW	11,856	2	11,856
	Heat exchanger [1]	371.0	m^2	42,159	1	42,159
	Tank [1]	41.2	m^3	31,776	1	31,776
	Browler [2]	9.0	m^3/s	180,000	9	1,620,000
	Truck [3]			23,744	1	23,744

[1] [30], [2] [29], [3] [53].

Regarding the COM values per kg of bioethanol, the baseline scenario ($4.0) is almost double the values for composting ($1.8) and lagooning ($1.7). Furthermore, externality costs for lagooning and composting were higher than in the baseline scenario. The 2G bioethanol coupled with biogas production incurs a total externality cost of about 2.15 $·kg^{-1}, while scenarios E + L and E + C have externality costs of 2.66 $·kg^{-1} and 2.85 $·kg^{-1}, respectively. Consequently, the baseline scenario has a COM with externalities of about $6.2 per kg of bioethanol, compared to $4.4 and $4.7 for E + L and E + C scenarios, respectively. Thus, the inclusion of externality costs in the COM leads to differences of up to 29% and 25% for lagooning and composting, respectively.

As for WSP values per kg of product, 2G bioethanol production reaches values of $2.12 and $2.29 in the lagooning and composting scenarios, respectively, which are closer to the reported values (e.g., 1.8 $·kg^{-1}). Considering the biorefinery design, the economic perspective could favour traditional vinasse management approaches (i.e., lagooning or composting). However, it is pertinent to consider the environmental impacts of these strategies.

3.2. Environmental Performance of 2G Apple Bagasse-Based Bioethanol

The environmental profile of 2G bioethanol production based on apple pomace is presented in Table 4. These results underscore the relevance of analysing the contributions of each stage in the product system, since significant environmental impacts are detected. Key stages within the biorefinery platform emerged as primary contributors to various impact categories (see Figure 6). For example, the fermentation section stands out as a critical hotspot in the GW, PMF, TA, FE, HCT, and FRS categories, due to the energy requirements of the distillation process, which includes steam and cooling water. It is worth mentioning that, in this scenario, the external steam supply is assumed to come from cogeneration systems, explaining the high relevance of this stage in the LU category, as this approach avoids reliance on fossil energy sources. The steam generation process is a hotspot in FET, MET, and HNCT categories, due to the final treatment of boiler ash.

Table 4. Environmental profile of 2G bioethanol based on FUs evaluated.

Impact Category	Acronym	Unit	Mass FU (1 kg)	Energy FU (1 MJ)	Volume FU (1 L)
Global Warming	GW	kg CO_2 eq	1.13	0.05	1.18
Stratospheric ozone depletion	SOD	mg CFC11 eq	1.19	0.05	1.25
Ionizing radiation	IR	Bq Co-60 eq	5.84	0.25	6.09
Ozone formation, Human health	OF, HH	g NOx eq	8.51	0.37	8.88
Fine particulate matter formation	PMF	g $PM_{2.5}$ eq	13.38	0.58	13.96
Ozone formation, Terrestrial ecosystems	OF, TE	g NOx eq	8.57	0.37	8.94
Terrestrial acidification	TA	g SO_2 eq	7.25	0.31	7.57
Freshwater eutrophication	FE	g P eq	0.87	0.04	0.91
Marine eutrophication	ME	g N eq	0.10	0.004	0.11
Terrestrial ecotoxicity	TET	kg 1.4-DCB	3.35	0.15	3.50
Freshwater ecotoxicity	FET	kg 1.4-DCB	0.08	0.004	0.08
Marine ecotoxicity	MET	kg 1.4-DCB	0.10	0.005	0.11
Human carcinogenic toxicity	HCT	kg 1.4-DCB	0.05	0.002	0.05
Human non-carcinogenic toxicity	HNCT	kg 1.4-DCB	3.22	0.14	3.35
Land use	LU	m^2a crop eq	1.16	0.05	1.21
Mineral resource scarcity	MRS	g Cu eq	0.27	0.01	0.27
Fossil resource scarcity	FRS	kg oil eq	0.33	0.01	0.34
Water consumption	WC	m^3	1.84	0.08	1.92

For the CED indicator per MJ of 2G bioethanol, non-renewable sources accounted for 0.60 MJ, while renewable sources contributed 1.32 MJ, mainly due to the use of biomass (1.19 MJ). Figure 7 displays each stage's contribution to the CED profile. The fermentation section stands out in fossil and renewable resources (wind, solar, hydro) due to its electricity demand, which is motivated by the diverse production of the Chilean electricity mix (mainly coal, solar and hydro, mainly). The purification section is the main contributor to biomass resource use (both fossil and renewable) due to steam demand during the distillation process, relying on cogeneration systems that consume wood chips. Finally, vinasse treatment for biogas production is another hotspot in fossil fuel use due to polymer demand (for thickening), which depends on the plastics industry in its upstream life cycle.

Bioethanol production has been widely studied in the literature using different feedstocks and valorisation routes. When comparing the environmental profile of 2G apple-based bioethanol in terms of the GW category, a broad range of values is observed. For instance, Muñoz et al. [54] evaluated different feedstocks such as maize grain and maize stover in the USA, sugarcane in Brazil, and sugar beet and wheat in France under a cradle-to-gate approach, obtaining CO_2eq emissions ranging from 0.7 to 1.5 kg per kg ethanol. González-García et al. [55] analysed the production of bioethanol and xylo-oligosaccharides from barley straw and brewer's spent grains under a cradle-to-gate approach, estimating an overall warming potential of 7.39 kg CO_2eq per kg product, where autohydrolysis pre-treatment was identified as the environmental hotspot.

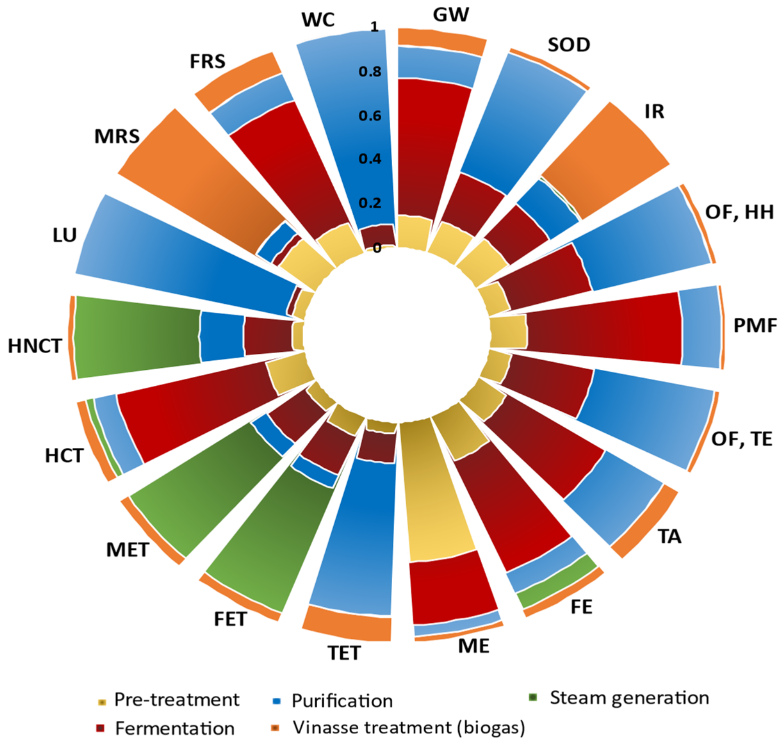

Figure 6. Stage contribution in the environmental profile of 2G bioethanol (baseline).

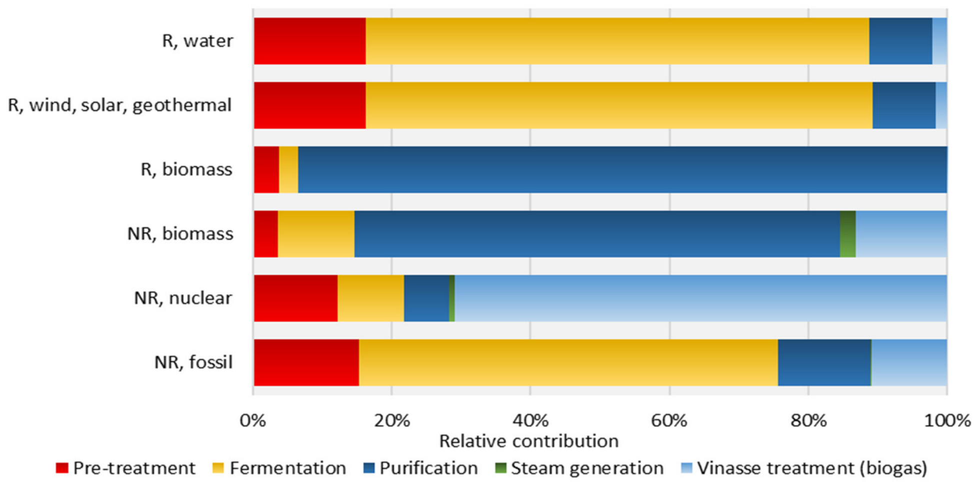

Figure 7. Stage contribution of bioethanol production in the CED indicator. (NR—Non-renewable; R—Renewable).

Similarly, Lyu et al. [56] evaluated production from cassava root, cassava straw and whole-plant cassava, resulting in emissions of 1.74, 2.93, and 1.55 kg CO_2eq per L of product, respectively. Findings by Wang et al. [57] align those of Lyu et al., whose work, using sweet potato, resulted in a carbon footprint of 1.47 kg CO_2eq per L of product, higher than the profile obtained in this work (1.2 kg CO_2eq per L). Furthermore, Morales-Vera et al. [58] evaluated the use of short rotation woody crop (poplar biomass) under a cradle-to-grave approach, obtaining a GW value of −1.05 g CO_2eq per MJ, by accounting for environmental credits from carbon sequestered during biomass cultivation and avoided fossil fuel emissions due to electricity surplus of the system.

Figure 8 presents a comparison of bioethanol's environmental profiles across different vinasse treatment scenarios. From this, it is evident that the E + B (baseline) scenario is the best alternative in nearly all impact categories, except in IR and MRS, and marginally in WC. This is primarily due to polymer consumption for thickening in the AD process. In the GW category, bioethanol emissions increase to 3.94 and 4.09 kg CO_2eq per kg of product for lagooning and composting, respectively. In addition, scenario E + B shows the greatest reductions in GW (72%), SOD (98%), and TA (64%) relative to composting (i.e., the worst-case scenario). In the E + C scenario, composting is the main contributor in the profile of the 2G bioethanol in categories such as GW (71%), SOD (97%), and TA (60%), while in the E + L scenario, lagooning is the critical factor in the GW category with about 70%.

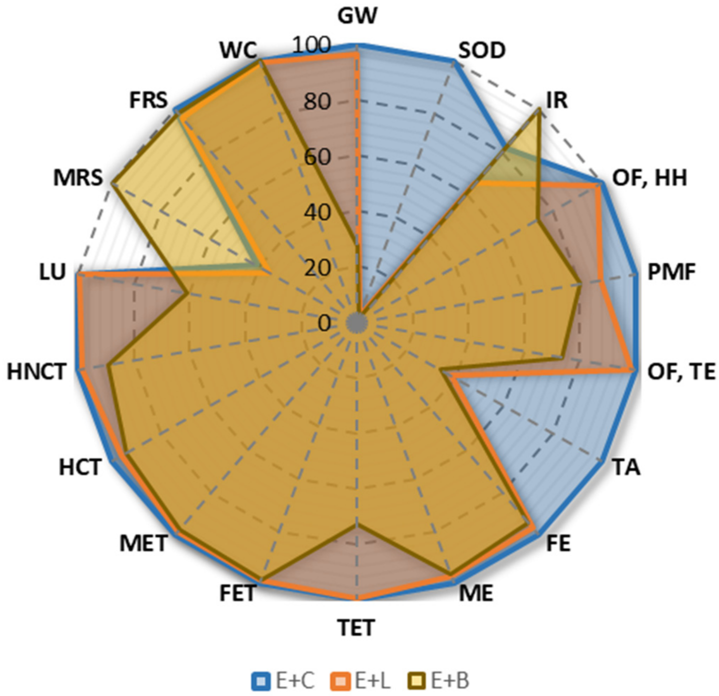

Figure 8. Comparison of the environmental profiles of 2G bioethanol scenarios evaluated (E + B—ethanol and biogas; E + L—ethanol and lagooning, E + C—ethanol and composting).

3.3. Eco-Efficiency Analysis

An eco-efficiency analysis was conducted to determine the optimal biorefinery design for 2G bioethanol production in terms of vinasse treatment (see Table 5). Considering cost-benefit perspectives, the base scenario proved to be the most eco-efficient in almost all categories, with the only exception of MRS. Although biogas production from stillage treatment represents the highest cost alternative due to investment requirements, it reduces the energy demand of the platform by offsetting biomass or fossil resource consumption. In addition, the effluent post-treatment ensures safe effluent discharge, reducing impacts in water-related categories. The economically favourable alternatives for the vinasse treatment (i.e., E + L and E + C) were not recommended from an eco-efficiency perspective. Their high direct CO_2 and CH_4 emissions contribute significantly to the GW category, which makes these options unsuitable for implementation.

Although large-scale co-production of 2G bioethanol and biogas from apple pomace is environmentally beneficial, it poses economic challenges. Therefore, the E + B scenario requires further research to enhance production yield of the biorefinery and identify potential co-products to achieve a financially viable system. Furthermore, public sector support could be crucial for implementing vinasse valorisation for energy purposes, especially regarding cost support.

Table 5. Eco-efficiency results of 2G bioethanol with the different vinasse treatment.

Impact Category	Unit	COM			Benefits		
		E + B	E + L	E + C	E + B	E + L	E + C
GW	$\$\cdot$kg CO_2 eq^{-1}	3.53	0.42	0.44	8.55	0.96	1.00
SOD	$\$\cdot$mg CFC_{11} eq^{-1}	3.35	1.01	0.02	8.10	2.30	0.06
IR	$\$\cdot$Bq Co-60 eq^{-1}	0.68	0.44	0.37	1.66	1.00	0.85
OF, HH	$\$\cdot$kg NOx eq^{-1}	469.54	146.73	154.06	1136.33	333.05	351.82
PMF	$\$\cdot$kg $PM_{2.5}$ eq^{-1}	298.53	114.01	106.67	722.46	258.78	243.59
OF, TE	$\$\cdot$kg NOx eq^{-1}	466.42	145.81	153.10	1128.78	330.96	349.62
TA	$\$\cdot$kg SO_2 eq^{-1}	550.81	205.42	84.21	1333.01	466.29	192.30
FE	$\$\cdot$g P eq^{-1}	4.60	1.87	1.93	11.12	4.25	4.41
ME	$\$\cdot$g N eq^{-1}	39.07	16.20	16.78	94.56	36.76	38.31
TET	$\$\cdot$kg 1,4-DCB^{-1}	1.19	0.36	0.39	2.88	0.83	0.88
FET	$\$\cdot$kg 1,4-DCB^{-1}	52.93	22.13	23.33	128.09	50.22	53.27
MET	$\$\cdot$kg 1,4-DCB^{-1}	38.62	15.97	16.83	93.46	36.25	38.44
HCT	$\$\cdot$kg 1,4-DCB^{-1}	76.69	31.40	32.18	185.60	71.28	73.50
HNCT	$\$\cdot$kg 1,4-DCB^{-1}	1.24	0.47	0.50	3.01	1.07	1.13
LU	$\$\cdot$m^{2}a crop eq^{-1}	3.44	0.88	0.94	8.34	2.00	2.14
MRS	$\$\cdot$g Cu eq^{-1}	14.99	17.54	16.25	36.28	39.82	37.10
FRS	$\$\cdot$kg oil eq^{-1}	12.29	5.24	5.38	29.73	11.89	12.28
WC	$\$\cdot$m^{-3}	2.17	0.91	0.97	5.25	2.07	2.21

E + B: ethanol and biogas; E + L: ethanol and lagooning, E + C: ethanol and composting. Colours definition: Red = worst, Yellow = intermediate, Green = best.

4. Conclusions

This manuscript evaluated the economic and environmental feasibility of using apple pomace for the co-production of bioethanol and biogas, with the latter used to reduce the energy demand of the biorefinery platform. Environmentally, the impact profile of 2G bioethanol align with previous studies in the literature. Different sections of the biorefinery contributed variably to environmental impact depending on the category. For example, the fermentation section showed high impacts in categories such as GW, PMF, HCT, and FRS, while purification has the highest impact in WC, LU, TET, and OF.

In terms of techno-economic analysis, vinasse treatment was the main contributor to both investment and operating costs (about $183 MM). Thus, the minimum selling price of bioethanol (5.7 $\$\cdot$kg^{-1}) is not commercially competitive in the current market. Lower bioethanol prices could potentially be achieved through non-energy strategies, such as lagooning and composting; however, these alternatives face limitations due to their higher environmental burden. Hence, the most eco-efficient scenario was the biorefinery design for the co-production of bioethanol and biogas. While this second-generation bioethanol process is environmentally feasible, economic barriers and the low sugar content of apple pomace remain key challenges for implementation. Future studies should focus on identifying additional co-products to enhance the economic viability of apple pomace.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/resources13110156/s1, Table S1: Workers per shift for representative unit operations; Table S2: Cost of utilities provided by off-sites for a plant; Table S3: Cost of raw materials; Table S4: Cost of waste treatment; Table S5: Life Cycle Inventory for bioethanol production based on 1 t of bioethanol; Table S6: Inventory data for lagooning treatment of 1 t of vinasse; Table S7: Inventory data for composting treatment of 1 t vinasse.

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