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Techno-economic analysis and life cycle assessment of pineapple leaves utilization in Costa Rica

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Abstract: Pineapple production around the world creates large amounts of wasted organic residue, mainly in the form of pineapple leaves. Current management practices consist of in situ decomposition or in situ burning, both of which cause proliferation of flies and air pollution, respectively. The research conducted aims to develop a utilization process for this residue. Considering that pineapple leaves are rich in carbohydrates and other nutrients, a simple biological process involving a two-step procedure for juice production and ethanol fermentation has been developed to convert the leaves into renewable fuel and spent yeasts for animal feed. The liquid fraction extracted from the leaves is used as the nutrients to culture a yeast, *Kluyveromyces marxianus*, for ethanol and yeast protein production. In Costa Rica, one of the major pineapple producing countries in the world, the studied process can produce 92708 and 64859 tons of bioethanol and spent yeast per year respectively, from its 44500 hectares of pineapple plantation. This techno-economic analysis indicates that a regional biorefinery with the capacity to produce 50000 metric tons per year of ethanol could have a short payback period of 4.72 years. The life cycle analysis further demonstrates the advantages of the studied biorefining concept over the current practice of open burning.

Keywords: Ananas comosus; bioethanol; fibrous material; mass and energy balance; life cycle assessment; protein

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1. Introduction

Costa Rica is one of the main pineapple producers and exporters in the world. The pineapple production in Costa Rica was 2.2 million metric tons (MMT) in 2019, which was about 9.4% of the production worldwide [1]. Commercial pineapple plantations follow a 2-year fruit crop cycle. Every other year, after harvesting the fruits, the plants (mainly leaves) need to be removed or treated immediately; otherwise, the residues may cause soil contamination or be capable of hosting the larvae of stable flies (*Stomoxys calcitrans*), threatening the health of the local cows, sheep, pigs, and people [2]. Additionally, efforts to turn pineapple waste into animal feed are limited by storage life and arduous procedures [3]. As a result, pineapple residue is dealt with as quickly as possible, usually in the form of open burning. This practice pollutes the groundwater and affects air quality [4]. Onsite decomposition, another residue removal approach, takes a long time and leaves the farms prone to pests, fire outbreaks, and diseases [5,6]. In general, an issue that plagues pineapple farms and the industry is the disposing of supposed pineapple waste in the form of inedible leaves. Thus, pineapple waste has long been dealt with as an inconvenient and useless byproduct by farms.

Meanwhile, pineapple residue consists of notable levels of cellulose, hemicellulose, and soluble mono-sugars [7]. Based on a pineapple leaf utilization process developed by authors, fresh pineapple leaves can be fully utilized to produce bioethanol and animal feed at the same time, eliminating its negative environmental impacts [8]. The juice in the fresh leaves was separated for yeast ethanol production; the leftover fibers can be burned to generate power for onsite uses. The resulting spent yeast after fermentation can be used as animal feed (Figure 1). *Kluyveromyces marxianus* was selected to produce ethanol and yeast protein. It was selected for its admirable thermotolerance and wide breadth of materials/substances that it can process (like lactose and xylose), as well as how quickly it grew. Additionally, *K. marxianus* produces different enzymes (phytase [9], β-galactosidase [10], inulinase [11], and polygalacturonases [12]) that will assist in the conversion of organic residue into valuable resources. Moreover, *K. marxianus*, one of the Generally-Regarded-As-Safe (GRAS) yeast species originally selected from cheese production, has potential as a probiotic yeast and as a food additive for humans and animal feed [13].

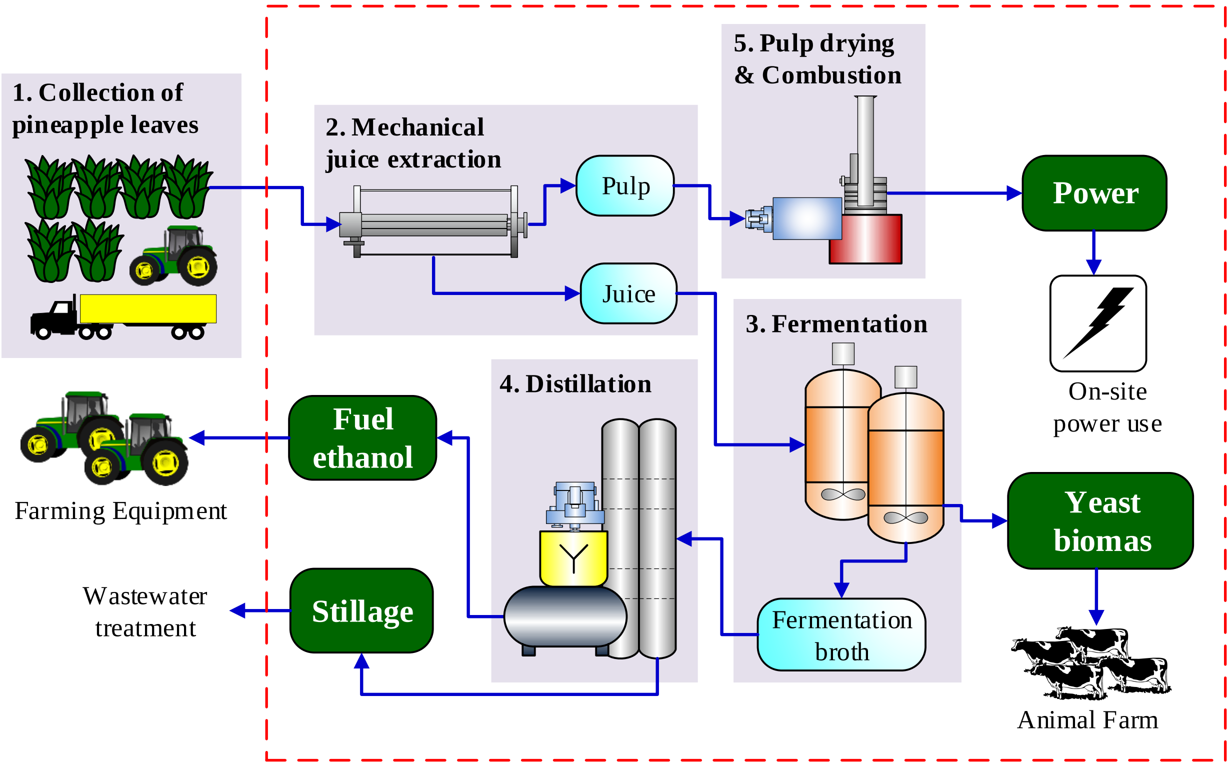

Figure 1. Pineapple leaf biorefining *

*: The red frame is the boundary for the life cycle assessment

The objective of this study is to develop a technically feasible and economically pineapple residue utilization process and pioneer a path towards sustainable clean energy in organic produce markets. Comprehensive techno-economic analysis with a detailed life cycle impact assessment is conducted to conclude a regional biorefinery of pineapple leaves utilization in Costa Rica.

2. Materials and Methods

2.1. *Feedstock and location of the biorefinery*

Costa Rica has approximately 44500 hectares of pineapple plantation across the country, generating more than 5.6 million tons of wet pineapple plant residue annually [8]. There are three main pineapple production regions in Costa Rica, the Huetar Norte region (49% of the total pineapple plantation in Costa Rica), the Atlantic Huetar region (29% of the total), and the Pacific region (22% of the total) [14]. This study selected the Huetar Norte region as the location to evaluate the economic and environmental impacts of a pineapple leaf biorefinery on the country. The pineapple residue (leaves) removed from local farms in the region are collected and transported to the biorefinery, and used as the feedstock to produce fuel ethanol, electricity, and animal feed. The detailed characteristics of pineapple leaves are listed in Table 1.

Table 1. Characteristics of pineapple leaves [8]

Parameter	**Leaf**	**Juice**	**Pulp**
Total solids (%)	13.8	6.2	51.6
Cellulose (% TS)	22.6	--	36.8
Hemicellulose (% TS)	26.1	--	28.1
Lignin (% TS)	7.3	--	5.1
Crude Protein (%TS)	6.9	14	5.7
Crude Fat (%TS)	3.0	3.5	4.0
Potassium (%TS)	2.6	3.76	0.56
Nitrogen (%TS)	1.1	2.24	0.912
Phosphorus (%TS)	0.11	0.18	0.08
Sulfur (%TS)	0.13	0.21	0.06
Ash (%TS)	6.1	10.02	1.65

2.2. *The biorefinery of pineapple leaf utilization*

A detailed mass and energy balance is needed to generate data for economic analysis and life cycle assessment of pineapple leaf utilization. According to the research outcomes from a previous study [8], the pineapple leaf biorefinery includes five units of operation; 1) leaf collection and transportation, 2) mechanical juice extraction, 3) juice fermentation, 4) distillation, and 5) pulp drying and combustion (Figure 1). The leaves are collected and transported to the biorefinery, where a mechanical juice extraction unit is used to extract the juice and produce pulp. Then, the pulp is dried and combusted to generate electricity in a boiler-turbine-generator system. The nutrient-rich juice is then used for yeast fermentation of ethanol and yeast biomass accumulation. The batch fermentation is carried out at a temperature of 35 °C and takes 24 hours. No nutrient supplementation is required, and the pH is not regulated.

After the fermentation, yeasts are settled out, dried, and packed as protein-rich animal feed. The broth is distilled to generate fuel ethanol. The thin stillage from the distillation of the broth is dilute. The COD of the thin stillage is less than 5000 mg/L, which is much lower than the thin stillage from the corn ethanol process (ranging from 74000 – 131000 mg/L of COD) [15]. Traditional stillage evaporation or anaerobic digestion processes are not suitable for such a dilute stream. Therefore, the activated sludge process is adopted to treat the dilute thin stillage before discharging. The mass and energy balance analysis is based on individual unit operations during the refining process and determines the size of individual unit operations following economic analysis and life cycle assessment.

2.3. *Economic assessment*

Data from a previous study was used to conduct the techno-economic analysis (TEA) to investigate the feasibility of such a biorefining concept in Costa Rica [8]. Considering the fact that the Huetar Norte region has nearly 50% of the total pineapple plantation in Costa Rica, the size of the biorefinery is set at an annual ethanol production of 50000 metric tons along with electricity and yeast biomass production. Correspondingly, 3000000 metric tons of wet leaves (besides all pineapple residues available in Huetar Norte region, additional 256 000 tons of biomass are shipped from nearby region to satisfy the feedstock demand of the biorefinery) need to be collected and transported to the biorefinery. Capital expenditure (CapEx) includes individual equipment costs and added direct and indirect costs. CapExs of fermentation and distillation, utilities, and wastewater treatment are linearly scaled using daily ethanol production as the base from reference numbers [16, 17]. CapEx of boiler and generator is linearly scaled using energy demand as the base from reference numbers [17]. CapExs of pulp drying and yeast drying are based on a reference CapEx number of $22/kg water removed/hr for a triple-pass rotary dryer [18]. The added direct and indirect cost in the CapEx is calculated using the number of 45% of total capital investment [17]. Operating expenditure (OpEx) includes energy costs of individual unit operations, maintenance costs, and labor costs. Energy costs are calculated based on energy consumption numbers from the mass and energy balance analysis. The local electricity cost in Costa Rica is $0.15/kWh. The diesel cost in Costa Rica is $0.94/kg. The maintenance cost is set at 2% of total equipment cost without considering added direct and indirect costs. Labor costs are all based on the local market price. The labor burden is set at 90% based on the current local rate. Revenues include fuel ethanol, electricity, and yeast biomass as animal feed. The electricity generated from the refinery is sold to the national grid, while residual heat of the turbine electricity generation is used for drying and distillation processes. The Modified Accelerated Cost Recovery System (MACRS) [19] a depreciation method that is used by the business in the U.S., was adopted to calculate the annual depreciation of CapEx considering the local government allows business owners to adopt and justify their depreciation method. Annual inflation of 3.2% was set for OpEx and revenues based on the five-year average inflation rate in Costa Rica (from 2016 to 2020). The net cash flow based on depreciated CapEx, inflated OpEx and revenues was calculated to determine the discounted payback period of the regional pineapple leaf biorefinery. In addition, a sensitivity analysis was also conducted to elucidate the effects of key unit operations on the payback period of the biorefinery.

2.4. *Life cycle assessment*

With the detailed mass and energy balance analysis, a life cycle assessment was carried out to elucidate the influences of implementing the biorefinery to Costa Rica on the reduction of carbon emission and improvement of air quality. The current pineapple leaf management practice of open burning was used as the control. Mass and energy flow from the mass and energy balance analysis are used to establish a life cycle inventory. The boundary of the life cycle assessment is from pineapple leaves after pineapple harvesting (without considering the pineapple plantation) to the end products of ethanol, dry yeast biomass, and reclaimed water. Equipment in the process and pineapple plantation are not included in this assessment. Four impact categories related to carbon emission and air quality were chosen to run life cycle impact assessment: global warming potential (GWP), particulate matter (PM), smog potential (SP), and air acidification potential (AAP). These four parameters are used to compare impacts on carbon emission and air quality between the biorefinery solution and the current practice of open burning. The classification of each category is defined by the US Environmental Protection Agency (US EPA) [20]. The analysis was conducted using the data from EPA's TRACI-2 characterization factors [21] and the Co-ordinated European Programme on Particulate Matter Emission Inventories (CEPMEIP) [22]. Contribution analysis was performed to interpret the factors that influence each impact category.

3. Results and Discussion

3.1. Mass and energy balance

Mass and energy balance analysis was conducted on the biorefining concept of whole pineapple leaf utilization (Figure 2 and Table 2). Since the pineapple leaves available in the Huetar Norte region are within a 100 km radius (considering 12 hours to harvest, collect and transport the biomass), a reference number of 200 kJ/kg wet residues was used to calculate fuel consumption for biomass collection and transportation (12 MJ/kg ethanol produced) [23]. The corresponding amount of fuel ethanol equivalent is 0.45 kg/kg ethanol produced.

Once the leaves biomass arrives at the biorefinery, the wet biomass is first crushed by an extraction unit to release nutrient-rich juice for ethanol fermentation. The mechanical extraction produces 46 kg of juice (containing 0.6 g/L and 16.4 g/L of C6 and C5 sugars, respectively) and 11 kg of wet pulp. There is 3 kg of wet leaves lost during the extraction process. The juice is also rich in proteins and other nutrients to support yeast growth for ethanol production. Mechanical juice extraction is an energy-intensive process. Energy consumption for the mechanical extraction is 23.6 MJ/kg ethanol produced (Table 2), which is the largest energy-demanding operation among all five-unit operations. From the mass balance, 60 kg of wet leaves are needed to produce 1 kg of ethanol.

The extracted juice (46 kg), without using any additional nutrients, is used for ethanol production; *Kluyveromyces marxianus* is the yeast strain to carry out the fermentation [8]. During a 24-hour culture under 35°C, 35 kg of fermentation broth with an ethanol content of 3.6% (v/v) and 11 kg of wet yeast are generated. Electricity and thermal energy consumptions for ethanol fermentation are 73.2 kJ/kg and 455.4 kJ/kg fermentation broth, which were calculated based on a reference [24]. Additionally, the process requires 255.0 kJ/kg fermentation broth (9 MJ/kg ethanol produced) for prior juice sterilization. Total energy consumption for ethanol fermentation is 18.5 MJ/kg ethanol produced (Table 2).

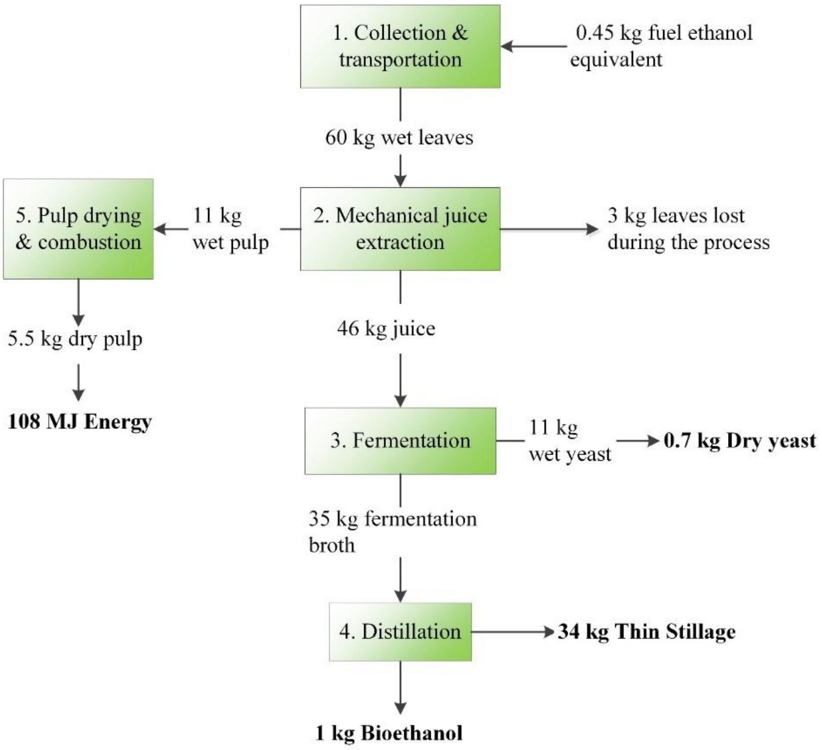

Figure 2. Mass balance of 1 kg ethanol production from pineapple leaves

Table 2. Energy balance of a regional pineapple leaf biorefinery [a, b]

Energy demand	**Energy (MJ/kg ethanol produced)**
1. Leaves collection and transportation [c]	-12.0
2. Mechanical juice extraction [d]	-23.6
3. Fermentation [e]	-18.5
4. Distillation [f]	-18.5
5. Pulp drying and combustion [g]	-14.7
6. Yeast drying [g]	-26.5
7. Wastewater treatment of stillage [h]	-0.51
Energy production	**Energy (MJ/kg ethanol produced)**
3. Fermentation [i]	8.9
4. Distillation [j]	10.9
3. Distilled ethanol [k]	26.7
5. Pulp combustion [l]	106.7
Overall energy balance	
Net energy [m]	38.9

a. Energy balance calculation is based on the ethanol production of 1 kg.

b. Negative numbers are energy demand, and positive numbers are energy generation.

c. The energy demands of 176 and 24 kJ/kg wet residues for leaves collection and leaves transportation, respectively, are referred from a study of sugarcane residue collection and transportation [23]. Ethanol heating value of 26.7 MJ/kg was used to calculate the fuel consumption for the pineapple leaf collection and transportation.

d. The electricity consumption of the mechanical juice extraction was 394 kJ/kg wet leaf [8].

e. Ethanol fermentation includes seed culture and ethanol fermentation. The energy consumption of 97.7 and 54.73 kJ/kg fermentation broth for seed culture and ethanol fermentation, respectively, was calculated based on a biorefining model [24].

f. The energy consumption (mainly thermal energy with 2% of parasitic electricity energy) is 18544 kJ/kg ethanol [25].

g. Triple-pass rotary dryers are used for both drying operations. The temperature of the initial biomass (pulp or yeast) is 35°C. The drying temperature is 100°C. The specific heat capacity of water and dried biomass are 4.18 and 1.48 kJ/kg·K, respectively. The latent heat of water at 100°C is 2244 kJ/kg. The parasitic electricity is 2% of the total thermal energy. The energy consumption was calculated based on a biorefining model [24].

h. The energy demand is based on typical electricity consumption for a municipal wastewater treatment operation (0.414 kWh/m^3 wastewater) [29]. The chemical oxygen demand of the stillage (5000 mg/L) is 10 times stronger than regular sewage (300-500 mg/L). The energy demand of the stillage treatment is corresponding increased to 4.14 kWh/1000 kg.

i. The heat recovery from the fermentation process is 60% of the thermal energy for sterilization.

j. The heat recovery from the distillation is 60% of the thermal energy for distillation.

k. The low heating value of ethanol is 26.7 MJ/kg.

l. The low heating value of dry pulp is 19.4 MJ/kg [8].

m. Net energy = Energy production – Energy demand.

A distillation tower is then used to extract ethanol from the fermentation broth. The distillation also generates 34 kg of stillage/kg ethanol, which is then treated by a wastewater treatment operation before discharging. Based on ethanol content in the fermentation broth (3.6%v/v), an energy demand of 18.5 MJ/kg ethanol produced for the distillation was calculated according to a reference [25] (Table 2). The amount of thermal energy recovered from the distillation is 11 MJ/kg ethanol produced, which is used for the sterilization stage. The wastewater treatment operation, applying a conventional activated sludge process, needs 0.51 MJ/kg ethanol produced to treat the stillage to satisfy the discharging standard.

Meanwhile, wet pulp and wet yeast are valuable products as well. The wet pulp has relatively high contents of cellulose (37%) and hemicellulose (28%) with a high heating value of 19.4 MJ/kg dry matter, which leads to a suitable feedstock for thermal energy generation. Yeast contains proteins (22%TS), carbohydrates (16%TS), and lipid (11%TS) [8], which is a high-quality animal feed. A triple-pass rotary dryer is used to dry both pulp and yeast separately. The drying process produces 0.70 kg dry yeast and 5.50 kg dry pulp per kg ethanol produced (Figure 2). The energy demands of drying pulp and yeast are 14.7 and 26.5 MJ/kg ethanol produced, respectively (Table 2). The dry pulp is further used as the feed by a combined heat and power unit (boiler and turbo-generator) to produce steam and electricity to power the biorefinery. Due to a large amount of dry pulp, the overall energy balance of the pineapple leaf biorefinery is positive. Net surplus energy of 38.9 MJ/kg ethanol produced was generated (Table 2).

According to the mass and energy balance analysis, the entire pineapple plantation (44500 hectares) in Costa Rica with an annual leaf production of 5562500 metric tons could produce net 92708 metric tons of fuel ethanol, 64859 metric tons of yeast biomass as animal feed, and 9892 TJ of potential energy generation (Table 3).

Table 3. Ethanol, fibrous material, and protein production of the studied biorefining process in Costa Rica

Parameter	**Value**
Pineapple plantation (hectare)	44500
Leaf residue production (wet metric ton/year) [a]	5562500
Total ethanol production (metric ton/year)	92708
Dry yeast biomass (metric ton/year)	64859
Potential energy generation (GJ/year) [b]	9892019
Electricity generation (GJ/year) [c]	2924872
Net energy generation (GJ/year) [d]	1066523

a. The pineapple leaf productivity is 125 wet metric tons/hectare/year.

b. The power generation (electricity and heat) is based on the total energy generation of the combustion of dry pulp.

c. The electricity generation is calculated using the efficiencies to convert the potential energy from dry pulp into electricity (84.48% and 35% for boiler and turbine-generator efficiencies, respectively) [30].

d. The net energy generation (electricity and heat) is calculated using the energy generated from the biorefining (without considering the energy content of product ethanol) to subtract the energy used by the biorefining.

3.2. *Economic analysis*

Economic feasibility is another important factor that determines the commercial applicability of such a pineapple leaf biorefinery in Costa Rica. The target biorefinery in the Huetar Norte region with an annual ethanol production of 50000 metric tons processes 300000 metric tons of wet leaves in the region. CapEx, OpEx, and revenues are the parameters to assess the economic performance of the biorefinery. As presented in Table 4, the CapEx to establish the studied biorefinery is $148101262 (not including the cost for land purchase or rental). Since a large amount of the pulp rich in cellulose and hemicellulose left is produced from the mechanical extraction and requires a significant power operation to handle them, the combined heat and power unit is the most expensive unit ($50809782) for the biorefinery. The wastewater treatment plant is the second most expensive unit ($13501106) because a substantial amount of the thin stillage requires a large footprint of the activated sludge unit. The total OpEx is $106236059/year, including feedstock collection and transportation, electricity cost (electricity for the biorefinery is purchased from the grid), maintenance, and labor costs. The revenue streams of the biorefinery are ethanol, dry yeast, and electricity from pulp combustion. Ethanol as a biofuel ($1.11/kg), dry yeast as an animal feed additive ($0.5/kg), and electricity ($0.15/kWh) lead to total revenue of $138727463/year, which is 1.31 times higher than the OpEx. Correspondingly, a net positive revenue of $32491404/year is realized from the biorefinery operation.

Table 4. Economic performance of a biorefinery with a capacity of 50000 metric ton ethanol per year from pineapple leaves in Costa Rica

Capital expenditure (CapEx)	Unit cost	Unit	Cost (USD)	Reference
Juice extraction [a]	$50000	2	$1000000	-
Ethanol fermentation [b]	$7800743	1	$7800743	[16]
Ethanol distillation [b]	$4348701	1	$4348701	[16]
Pulp drying [c]	$816200	1	$816200	[31]
Yeast drying [c]	$1293380	1	$1293380	[31]
Boiler and generator [d]	$50809782	1	$50809782	[17]
Utilities [e]	$1885782	1	$1885782	[17]
Wastewater treatment plant [f]	$13501106	1	$13501106	[17]
Added direct and indirect cost (45% of total CapEx) [g]	$66645568	1	$66645568	[17]
Total CapEx			**$148101262**	
Operational expenditure (OpEx)	**Unit cost**	**Unit**	**Cost (USD)**	**Reference**
Diesel fuel for leaves collection and transportation [h]	$0.94/kg for collection $21.53/kg for transportation	11601343 kg/year for collection 1584402 kg/year for transportation	$44965768 /year	[32]
Electricity for the juice extraction	$0.15/kWh	328333324 kWh/year	$49250197 /year	[33]
Electricity for the fermentation	$0.15/kWh	35593107 kWh/year	$5338966 /year	[33]
Electricity for the distillation	$0.15/kWh	5 050 167 kWh/year	$757525 /year	[33]
Electricity for the pulp drying	$0.15/kWh	3 990 419 kWh/year	$598563 /year	[33]
Electricity for the yeast drying	$0.15/kWh	7 216 700 kWh/year	$1082505	[33]

			/year	
Electricity for the wastewater treatment	$0.15/kWh	7 036 140 kg/year	$1055421 /year	[33]
Maintenance [i]	-	-	$1629114 /year	-
Labor cost	**Unit cost**	**Unit**	**Cost (USD)**	**Reference**
Plant manager	$50,000/ employee /year	1 employee	$50000 /year	[34]
Plant engineer	$40,000/ employee /year	2 employees	$80000 /year	[34]
Maintenance supervisor	$30,000/ employee /year	1 employee	$30000 /year	[34]
Maintenance technician	$25,000/ employee /year	8 employees	$200000 /year	[34]
Lab manager	$30,000/ employee /year	1 employee	$30000 /year	[34]
Lab technician	$20,000/ employee /year	3 employees	$60000 /year	[34]
Shift supervisor	$20,000/ employee /year	4 employees	$80000 /year	[34]
Shift operator	$15,000/ employee /year	16 employees	$240000 /year	[34]
Yard employee	$10,000/ employee /year	2 employees	$20000 /year	[34]
Clerk and secretary	$15,000/ employee /year	2 employees	$30000 /year	[34]
Labor burden [j]			$738000 /year	
Total labor cost			$1558000 /year	
Total OpEX			**$106236059 /year**	
Revenue	**Unit cost**	**Unit**	**Cost (USD)**	**Reference**
Ethanol	$1.11/kg	50000000 kg/year	$55500000 /year	Current price
Dry yeast	$0.5/kg	35000000 kg/year	$17500000 /year	Current price
Electricity for national grid [k]	$0.15/kWh	438183086 kWh/year	$65727463 /year	Current price
Total revenue			**$138727463 /year**	

Net revenue [l]	**$32491404 /year**
Payback time (years) [m]	**4.72**

a. The juice extraction unit is based on a unit with a capacity of 5000 metric tons/day. The costs of individual units were obtained from a vendor.
b. The number was linearly scaled using the ethanol production from the reference.
c. The cost of the triple-pass rotary dryer is calculated based on the capital cost of $22/kg water removed/hr.
d. The number was linearly scaled using the steam demand from the reference.
e. Utilities include equipment for water cooling/heating, electricity converter and transportation, and steam delivery etc. The number was linearly scaled using the ethanol production from the reference.
f. Wastewater treatment cost was linearly scaled using the ethanol production from the reference.
g. Added direct costs include warehouse, site development, and additional piping. Indirect costs include field expenses, home office and construction, proratable costs, and other costs.
h. The colletion cost of $0.94/kg diesel is for the fuel only. The transportation cost of $21.53/kg diesel include fuel, truck rental, and labor cost.
i. The maintenance cost is set at 2% of total equipment cost without considering added direct and indirect costs.
j. The labor burden is set at 90% of the total salary.
k. Electricity cost is calculated considering the conversion efficiency from burning dry pulp.
l. The net revenue = Total revenue – Total OpEx
m. The payback time is a discounted payback time.

The 5-year average local inflation of 3.2% at Costa Rica is used as the inflation rate. The depreciation period is set at 20 years. The depreciation is just on CapEx. The annual depreciation rates from MARCRS (Modified Accelerated Cost Recovery System) are: 0.100, 0.188, 0.144, 0.115, 0.092, 0.074, 0.066, 0.066, 0.065, 0.065, 0.033, 0.033 (after 10 years).

The cash flow analysis predicts that the discounted payback period of the biorefinery is 4.72 years, which is shorter than similar biorefineries [35,36]. In addition, the internal rate of return (IRR) for the project is 24.64% and the net present value (NPV) at 10% is $200 764 280, showing the profitability investment of the project. A sensitivity analysis was then conducted on four key items (from both CapEx and OpEx) of the boiler and generator unit, wastewater treatment unit, collection and transportation, and juice extraction to elucidate impacts on the payback period (Table 5).

A decrement of 25% on OpEx of the juice extraction could reduce the discounted payback period by 28% (4.7 to 3.4 years), which is the largest reduction among these four key items. The reduction on OpEx of the collection and transportation can also greatly decrease the discounted payback period by 26% to 3.5 years. A 25% reduction on CapEx of the boiler/generator and wastewater treatment could shorten the discounted payback period by 17 and 4.4%, respectively. According to the sensitivity analysis, improving the efficiency of mechanical juice extraction and reducing the cost of the leaves collection and transportation are two key factors to further enhance the economic performance of the biorefinery.

Table 5. Sensitivity analysis of key CapEx, OpEx, and revenue items on the discounted payback period of the biorefinery [a, b]

Item	Base value	Sensitivity range	Change on dynamic payback period
CapEx of the boiler/generator	$50809782	$38107337 - $63512228	16.5% - 16.5%
CapEx of the wastewater treatment	$13501106	$10125829 - $16876382	4.4% - 4.4%
OpEx of the collection and transportation	$44965768/year	$33724326 - $56207210	26.1% - 52.3%
OpEx of the juice extraction	$49250197/year	$36937648 - $61562746	28% - 60.4%

a. All values are adjusted by ±25% of their base values.

b. The base payback period is 4.72 years.

3.3. *Life cycle assessment*

Based on the mass and energy balance analysis, a life cycle inventory was developed for the biorefinery (50000 metric tons ethanol per year) and the on-site burning (Table 6). According to the inventory, life cycle assessments on the four impact categories of GWP, PM, AAP, and SP were analyzed using contribution analysis [26].

The global warming potential is the amount of greenhouse gases that are released during the life cycle of the process. Since pineapple leaves are plant material, CO_2 release from the combustion of the leaves is not counted as greenhouse gas emission, so that CO_2 emission from the on-site burning was not included in the GWP calculation.

Emission data of methane (CH_4) and nitrous oxide (N_2O) were normalized to a metric ton of CO_2 equivalent (CO_2-e) based on the following conversions: 1 kg CH_4 = 21 kg CO_2-e; and 1 kg N_2O = 310 kg CO_2-e [27]. Based on the calculation, the on-site burning has an overall GWP of 44339 metric tons of CO_2-equivalent, while the biorefinery has a negative GWP of -72965 due to the fact that the whole leaves have been processed to produce fuel, chemicals, and energy (Table 7). Distribution analysis demonstrates that N_2O and CH_4 from the burning contribute 56% and 44% of GWP, respectively (Figure 3). Renewable power generation and bioethanol production are the key contributors (33% and 67%, respectively) for negative GWP of the biorefinery. This result indicates that besides value-added commodity production, the biorefining concept can efficiently reduce greenhouse gas emissions from pineapple plantations.

PM contains microscopic solids or liquid droplets that can be inhaled and cause serious health problems. Crop residue burning is one of the main PM sources. The analysis on PM demonstrates that biorefinery greatly reduces PM emission from the on-site burning of the leaves on the field (Table 7). There is no PM emission from the biorefinery since fuel ethanol is used for leaves collection and transportation. The on-site burning releases 5951 metric tons/year of PM, which has been a major environmental issue in northern Costa Rica.

AAP is the potential change of atmospheric acidity caused by the release of SO_2, N_2O, and NO_x from biomass processing. Compounds that can cause air acidification are converted into metric ton SO_2-equivalent. The AAP is calculated based on: 0.21 kg of SO_2 released from burning one kg of pineapple leaves with 80% of dry matter; 0.21 kg of N_2O released from burning one kg of dry pineapple leaves; and 2.6 kg of NO_x released from burning one kg of dry pineapple leaves. AAP emission factors for SO_2, N_2O, and NO_x are 1, 0.7, and 0.7, respectively. Correspondingly, the life cycle assessment shows that there is no AAP from the biorefinery. The on-site burning releases 923 metric tons per year of SO_2-equivalent from the same amount of leaves used for the biorefinery (Table 7). Distribution analysis indicates that NOx from the burning is the dominant contributor (82%) to the overall AAP.

Smog is air pollution caused by the chemical reaction between sunlight, nitrogen oxides, and volatile organic compounds [28]. N_2O and NO_x are the main chemicals capable of smog formation with SP emission factors of 16.8 and 24.8 metric ton O_3-equivalent/ton substance). The study shows again that the studied biorefinery does not generate any compounds that have SP. Currently, on-site burning produces both gases (N_2O and NO_x) and leads to an SP of 28167 metric tons per year of O_3-equivalent (Table 7). NO_x contributes more than 94% of SP from on-site burning.

The life cycle impact assessment demonstrates the advantages of the studied biorefining concept over the current practice of open burning. The biorefining concept eliminates SP and AAP, significantly reduces PM emission, and leads to a negative GWP process to handle pineapple leaves.

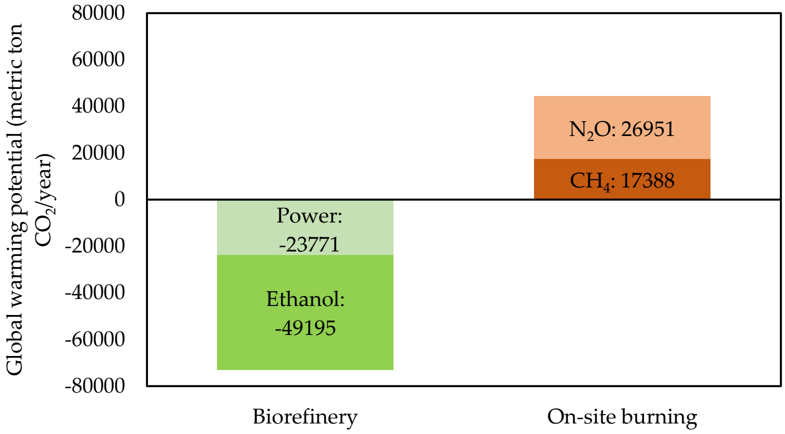

Figure 3. Contribution of global warming potential for the biorefinery and control on-site burning; (The GWP for the power does not include the ethanol product)

Table 6. Life cycle inventory of the biorefinery and on-site burning

Process	**Item**	**Value**	**Unit**	**Reference**
Raw material inventory	Pineapple leaves (wet amount)	3000000	Metric ton/year	-
	Total solids (TS) of pineapple leaves	13.8	%	-
On-site burning (Control)	Amount of pineapple leaves burned	80	% of TS	[37]
	CH_4 emission factor	1.6	kg CH_4/metric ton dry pineapple leaves burned	[38]
	N_2O emission factor	0.21	kg N_2O/metric ton dry pineapple leaves burned	[38]
	Particulate matter (PM) factor	11.5	kg/metric ton dry pineapple leaves burned	[39]
	SO_2 emission factor	0.21	kg SO_2/metric ton dry pineapple leaves burned	[39]
	NOx emission factor	2.6	kg NOx/metric ton dry pineapple leaves burned	[39]
Biorefinery	Energy consumption of the process	575000000	MJ/year	

CO_2 emission factor from energy consumption of the process	0.117	kg CO_2/MJ energy consumed	[40]
Net ethanol production	27500	Metric ton ethanol/year	-
Energy content of ethanol [a]	26.7	MJ/kg	-
Reduction factor of CO_2 emission from replacing gasoline fuel	0.067	kg CO_2/MJ fuel consumed	[40]

a. The low heating value of ethanol.

Table 7. Comparison of the life cycle impact assessment between the biorefinery (50,000 metric ton ethanol/year) and control on-site burning

Parameter	**Biorefinery**	**On-site burning**
Particulate matter potential (metric ton/year)	0	5951
Global warming potential (metric ton CO_2-e/year)	-71620	44339
Air acidification (metric ton SO_2-e/year)	0	923
Smog potential (metric ton O_3-e/year)	0	28167

4. Conclusions

As one of the largest pineapple producers in the world, Costa Rica produces large amounts of fresh pineapples and pineapple plant residues. This study comprehensively analyzed the environmental and economic impacts of a biorefining concept on pineapple leaf management. Pineapple leaves were first extruded to produce juice and fibrous material. The juice was fermented by a yeast, *Kluyveromvces marxianus*, to produce ethanol and yeast proteins. The techno-economic analysis concluded that implementing biorefining could utilize the annual leaf production of 556250 metric tons per year in Costa Rica and produce 92708 metric tons of fuel ethanol, 64859 metric tons of yeast biomass as animal feed, and 2924872 GJ of renewable electricity. Implementing yeast production as a secondary source of income benefits the pineapple industry and overcomes the elevated cost of biomass harvest and transportation.

Correspondingly, a biorefinery operation that utilizes 50 000 metric tons per year of ethanol can generate a net revenue of $32 491 404/year from products of fuel ethanol, renewable electricity, and yeast biomass. The life cycle assessment further concludes that biorefining can eliminate all negative environmental impacts currently related to the open burning of the leaves, yielding a net negative GWP and completely reducing PM emissions, AAP, and compounds containing SP. These factors all lead to a carbon-negative process. Therefore, this study concluded a technically feasible, economically sound, and environmentally friendly concept to utilize pineapple residues in Costa Rica, which will further facilitate the realization of the carbon neutrality goal and provide a technical approach to farmers to treat a residue with potential hazards to the environment and human health.

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C.L.; visualization, C.L.; supervision, M.B.; All authors have read and agreed to the published version of the manuscript.

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