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Process Design and Techno-Economic Feasibility Analysis of an Integrated Pineapple Processing Waste Biorefinery

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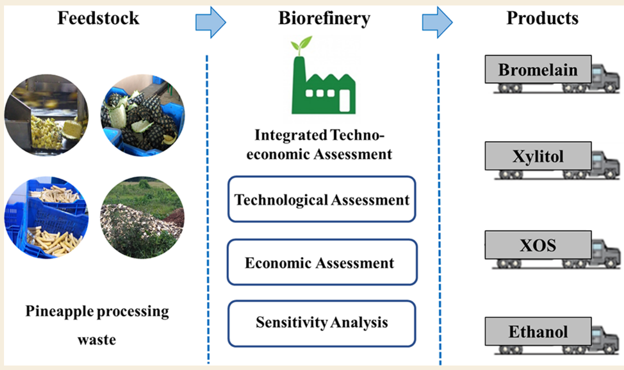
ABSTRACT: This study assesses the techno-economic feasibility of an integrated biorefinery based on pineapple processing waste. Xylooligosaccharides, ethanol, xylitol, bromelain, and silage are among the key products of the biorefinery. The economic performance of the processes involved in generating the biorefinery products was assessed based on calculations performed in ASPEN Plus. Seven different scenarios were designed with individual and multiple products and were further evaluated for a plant capacity of 10 tons per hour as the base case. Sensitivity analysis showed that plant capacity and selling price of value-added products were the most important factors that influenced plant economics. The plant capacity twice the base capacity often made the venture economically feasible as in the case of scenarios 1 (production of xylitol and silage) and 7 (production of bromelain, xylitol, and silage) with an NPV of \$9.2 million and \$8.9 million, respectively. Increasing the selling price of the products by 25% of the base case made scenarios 1 and 6 (production of bromelain, xylitol, ethanol, and silage) economically viable (NPV > 0). A decrease in the price for procurement of pineapple waste from \$25/ton to \$10/ton made scenario 4 (production of bromelain and silage) profitable with an NPV of \$3.3 million and IRR of 42%.



KEYWORDS: *pineapple processing waste, biorefinery, bromelain, xylitol, techno-economic model*

INTRODUCTION

The advancement of the bio-based economy over the dominant fossil-based economy highlights the requirement to shift toward sustainability to address the emerging environmental challenges.[1] Biorefineries are characterized as the leading example of a biobased economy. The biorefinery concept is very similar to a petrochemical refinery where different processes are integrated to obtain biofuels, biochemicals, heat, and power as the major value-added products from biomass.[2] Recent studies have focused upon valorization pathways for food processing wastes, specifically cereals, oil crops, fruits, vegetables, fish, meat, dairy, eggs, sugar crops, and tubers.[3,4] Most of the waste biorefinery concepts are broadly based upon single conversion processes to produce biobased chemicals and biofuels.[5] As reported in the literature, the technology readiness levels (TRL) are higher for the conversion of biomass into energy.[6] Since some of these technologies such as anaerobic digestion are implemented on a commercial scale, the real costs for a similar biorefinery are easily available. However, the biorefineries focused upon the production of biochemicals and value-added products present a lower TRL, and hence, the techno-economic assessment is difficult and uncertain.[7] Most of the economic analyses of individual biorefineries are conducted using commercial process simulators such as ASPEN Plus, SuperPro Designer, and others.[8,9] The economic viability of such biorefineries is assessed by integrating the fuel/energy production pathways along with those of value-added products and biochemicals. A few recent studies have reported the techno-economic feasibility assessment of biorefineries exclusively focused on fruit wastes such as citrus wastes,[10,11] olive wastes,[12] mango waste,[13] and spent pulp of berries.[14] To the best of authors' knowledge, there is no published work on techno-economic feasibility assessment for a pineapple processing waste biorefinery.

The global production of pineapples was estimated to be 28.3 million tons in 2018.[15] The annual production of pineapples in India and Australia is reported to be 1.7 million[16] and 0.076 million tons,[17] respectively, in 2018.

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Table 1. Composition of Different Fractions of Pineapple Processing Wastes

biomass component	values (% dry basis)			
	peels	crown	core	pomace
cellulose	20.9 ± 0.6	21.9 ± 1.1	40.3 ± 2.3	39.6 ± 2.9
hemicellulose	31.8 ± 1.9	33.1 ± 1.7	29.6 ± 0.9	30.8 ± 1.5
lignin	10.4 ± 1.0	13.6 ± 2.1	3.5 ± 0.06	2.9 ± 0.1
crude protein	3.9 ± 0.2	2.6 ± 0.3	0.9 ± 0.01	0.3 ± 0.01
total extractives	28.1 ± 2.5	20.8 ± 2.3	22.3 ± 0.3	22.6 ± 0.2
ash	5.1 ± 0.1	7.1 ± 0.1	3.7 ± 0.2	3.0 ± 0.3
organic matter	95.1 ± 0.1	92.8 ± 0.1	96.3 ± 0.2	96.4 ± 0.8

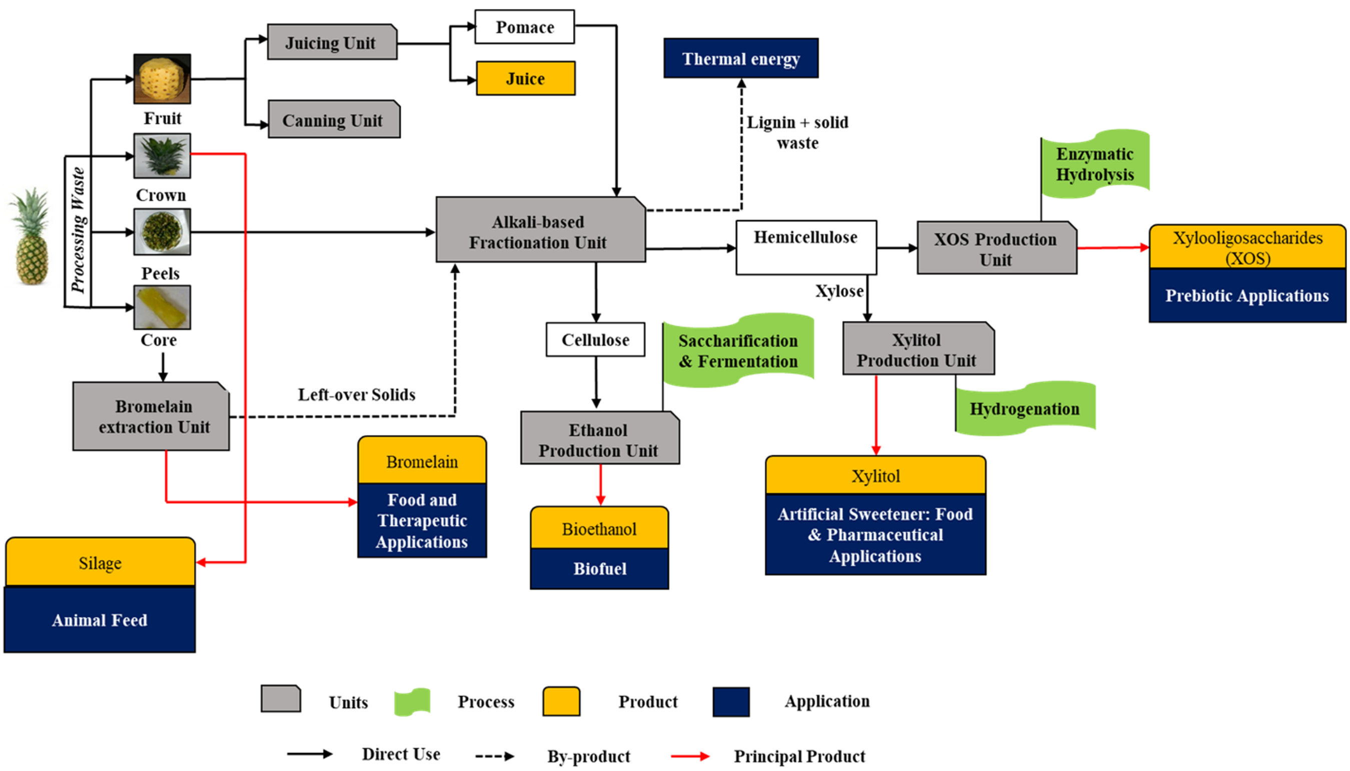

Figure 1. Process design for pineapple waste biorefinery.

Processing of the fruit for canned juice/slices accounts for a large quantum of waste (45−60% of the whole weight of fruit) in the form of crown, core, peels, and pomace.[18] The pineapple peels and core have been reported to be a good source of protease bromelain, which is known for its potential applications in the food and therapeutic sector.[19] The carbohydrate-rich residue can further be converted into bio-based chemicals such as bioethanol,[20] bio-butanol,[21] xylitol,[18,22,23] succinic acid,[24] lactic acid,[25] polyhydroxy butyrate,[26] and others.

The current research trends have shown that the concept of biorefinery and the production of biobased products will continue to be explored in the coming future. In the current study, a pineapple processing waste-based biorefinery model was developed wherein valorization pathways were modeled using computer-based simulations to estimate the energy inputs and the costs associated. Due to the unavailability of commercial biorefinery plants, assumptions were made based on the information obtained from pineapple processors, researchers, industry experts, and equipment suppliers of fruit processing industries. Inputs for process models were sourced from our experimental work at a laboratory scale wherein an integrated biorefinery approach was developed to recover and concentrate value-added products from pineapple waste.[23,27−29] The results from the technoeconomic assessment would assist the stakeholders to take informed decision regarding the valorization of pineapple processing wastes in an integrated biorefinery approach.

METHODOLOGY

Selection of Scenario

Region-specific analysis of the potential of pineapple waste is important for developing a sustainable biorefinery due to the existing large regional differences in quantity and quality of waste. It is expected that the size of the biorefinery in terms of the quantity of pineapple processing waste being processed should be feasible concerning the waste generated in a given area. Based on the available supply chain models of agricultural residues,[30] it was assumed that the waste gets collected within a 20 km radius from the plant, which would be more realistic and sustainable.

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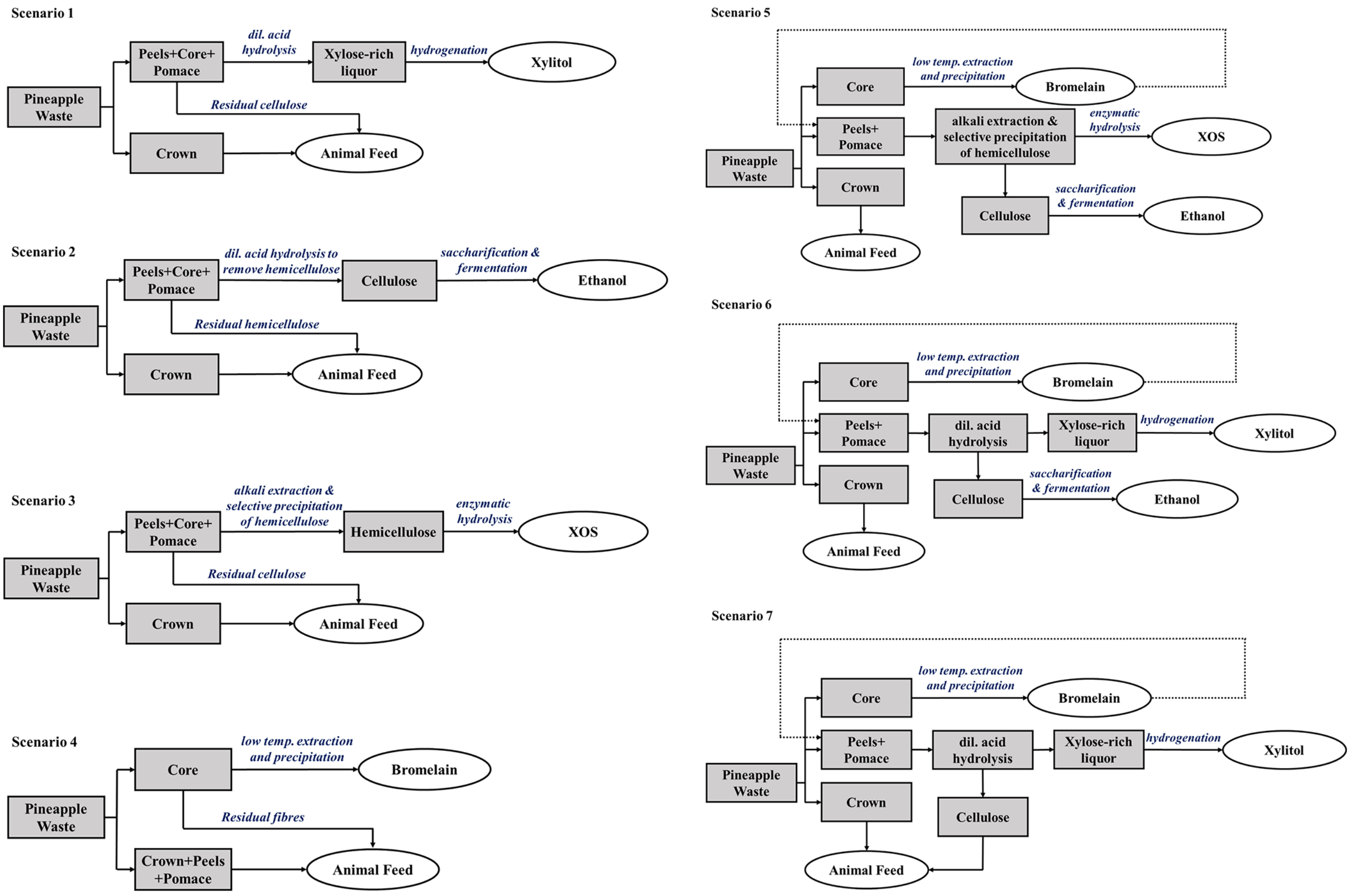

Figure 2. Scenarios for the valorization of pineapple processing wastes.[1−7]

Process Design and Conceptual Framework

In India, there is no formal mechanism to valorize pineapple processing waste. Field burning, composting, biogas generation, and the use of waste in the form of animal feed are popular ways to manage such waste. In recent times, several studies have reported different pathways to valorize this waste for the separation of individual components such as bromelain, polyphenols, biofuels, and other cellulosic biochemicals and bioproducts.[20,23,29,31−37] In our laboratory, we have attempted to develop an integrated approach for the production of high-value biochemicals from pineapple processing waste and achieving zero solid waste.[18,23,29]

In the Indian context, we have a very limited number of pineapple processing industries situated near the pineapple growing hubs. The large pineapple processing units process around 70,000−100,000 tons of pineapples in 5−6 months. Consequently, around 30,000−50,000 tons of waste is generated within 150−180 days of plant operation. On average, it is feasible to procure around 200−270 tons/day of waste from a large pineapple processing industry. The composition of pineapple processing waste fractions is given in Table 1.

Since pineapple is a seasonal fruit, the canning/juicing operation continues only for 5−6 months, and we assumed that the plant would operate for 24 h per day and 300 days per year (considering the provision of storing the pineapples in inventory for the lean period) with the processing of 240 tons of pineapples per day as the base case of 10 metric tons per hour (MTPH). A basic process diagram for the pineapple processing waste biorefinery is represented in Figure 1. The complete biorefinery involves an exhaustive set of unit operations, which increase the overall cost for running the biorefinery. To understand the effect of product selection on the economic feasibility of the pineapple waste biorefinery, the following seven scenarios were selected:

(i) Scenario 1: Xylitol and silage production.
(ii) Scenario 2: Ethanol and silage production.
(iii) Scenario 3: Xylooligosaccharides (XOS) and silage production.
(iv) Scenario 4: Bromelain and silage production.
(v) Scenario 5: Production of XOS, bromelain, ethanol, and silage.
(vi) Scenario 6: Production of xylitol, bromelain, ethanol, and silage.
(vii) Scenario 7: Production of xylitol, bromelain, and silage.

The schemes for the scenarios are given in Figure 2. Production of silage has been an integral part of all the scenarios considered in this study. However, for practical purposes, the complete conversion of the biomass into silage is not feasible due to the challenges associated with preparation of silage in warm climate conditions like in India.[38] Deterioration of the silage is an important issue in places with hot weather conditions because they often lead to butyric and alcoholic fermentation of the biomass.[38,39] The process design for the valorization of pineapple processing waste could be divided into four major categories given below:

Extraction of Bromelain. The process for extraction of bromelain involves blending of pineapple core waste with phosphate buffer (50 mM, pH 7.0) in the ratio 1:1 (w/w) for

Table 2. Total Capital Investment Cost for Biorefinery Scenarios 1 to 7 for the Year of Study 2020

summary of fixed capital estimates	factor of EPC	cost (USD) scenario 1	scenario 2	scenario 3	scenario 4	scenario 5	scenario 6	scenario 7
A. total plant direct cost								
1. equipment purchase cost (EPC)	100	8,244,100	6,140,900	6,064,400	330,400	6,546,300	8,777,500	8,479,300
2. installation	40	3,297,600	2,456,400	2,425,700	132,200	2,618,500	3,511,000	3,391,700
3. process piping	30	2,473,200	1,842,300	1,819,300	99,100	1,963,900	2,633,000	2,543,800
4. instrumentation	20	1,648,800	1,228,200	1,212,900	66,100	1,309,200	1,755,500	1,695,900
5. insulation	1	82,400	61,400	60,600	3300	65,500	87,800	84,800
6. electrical	10	824,400	614,100	606,400	33,000	654,600	877,700	847,900
7. buildings	40	3,297,600	2,456,400	2,425,700	132,200	2,618,500	3,511,000	3,391,700
8. yard improvement	5	412,200	307,000	303,200	16,500	327,300	438,900	424,000
TPDC		20,280,300	15,106,700	14,918,200	812,800	16,103,800	21,592,400	20,859,100
B. total plant indirect cost (TPIC)								
1. engineering	60	4,946,400	3,684,500	3,638,600	198,300	3,927,700	5,266,500	5,087,600
2. construction	85	7,007,500	5,219,800	5,154,700	280,900	5,564,300	7,460,900	7,207,400
TPIC		11,953,900	8,904,300	8,793,300	479,200	9,492,000	12,727,400	12,295,000
C. total plant cost (TPC) = TPDC + TPIC		32,234,200	24,011,000	23,711,500	1,292,000	25,595,800	34,319,800	33,154,100
D. contractor's fee and contingency (CFC)								
1. contractor's fee	19	1,566,400	1,166,800	1,152,200	62,800	1,243,800	1,667,700	1,611,100
2. contingency	38	3,132,800	2,333,500	2,304,500	125,600	2,487,600	3,335,400	3,222,100
CFC		4,699,200	3,500,300	3,456,700	188,400	3,731,400	5,003,100	4,833,200
E. direct fixed capital cost (DFC)								
DFC = TPC + CFC								
DFC		36,933,400	27,511,300	27,168,200	1,480,400	29,327,200	39,322,900	37,987,300

60 s.[29] The liquid is separated from the solid residue in a filtration tank followed by centrifugation at 10 °C for 10−15 min at 4500 rpm to get rid of the suspended solids and obtain a clear enzyme-rich extract. The residue is diverted into another stream for the valorization of its cellulose and hemicellulose content. Ethanol (95% v/v) is added to the enzyme-rich extract in the ratio 1:5 (v/v) and kept for overnight precipitation of enzyme bromelain.[29,40] The precipitated enzyme is filtered and subsequently freeze-dried.

Valorization of Hemicellulose Content: Production of XOS and Xylitol. The pineapple peel, pomace, and the core residue (left after extraction of bromelain) is dried at 50 °C and pulverized using a grinder for size reduction. The dried powder is easy to store for the smooth functioning of the industry during the off-season when the raw material is not readily available. Extractives are removed from the dried biomass by refluxing it with a 50% ethanol−water mixture with a solvent−solid ratio of 20:1 (v/w). After refluxing for 4 h, the liquid stream is diverted toward the distillation unit to recycle the ethanol and water mixture.[41] More than 95% of the ethanol is recovered from the ethanol−water mixture. The extractive-free biomass is then dried at 50 °C and then incubated with 10% (w/v) NaOH in a reactor for 1 h at 121 °C and 15 psi pressure.[23] The solution is separated from the cellulose-rich solid residue by filtration, which then goes into another stream for the production of bioethanol. The alkaline liquor is found to be rich in hemicellulose and lignin.[42,43] The pH of the alkaline liquor is set to 5.0, and the hemicellulose present in it is precipitated using 95% (v/v) ethanol.[44,23,45] The solution is kept for overnight precipitation. The precipitate is filtered and freeze-dried to obtain solid hemicellulose chunks, while the ethanolic liquor containing comparatively smaller amounts of sodium hydroxide, glacial acetic acid, and lignin is diverted toward the distillation unit to recycle back the ethanol and glacial acetic acid. The extracted hemicellulose is then enzymatically hydrolyzed to obtain XOS.[23,46−48] The major focus is upon xylobiose (DP2) and xylotriose (DP3), which are known for their maximum prebiotic potential. The maximum yield of XOS is obtained at 50 °C and pH 5.0 at the end of 24 h with an enzyme dosage of 15 U/mg of endo-xylanase.[23] The XOS mixture is then purified using membranes and freeze-dried.

In another process, the hemicellulose from the extractive-free biomass is valorized in the form of xylitol, which finds potential application as an artificial sweetener.[49] The extractive-free biomass is then treated with dilute nitric acid (0.5% v/v) at 121 °C for 1 h to obtain a cellulosic residue and a liquor rich in xylose.[23] The xylose-rich liquor is converted into xylitol by catalytic hydrogenation.[50−52] Industrial production of xylitol via hydrogenation of wood hydrolysates under high pressure in the presence of Raney nickel as a catalyst is well reported in the literature.[53,54] The retail price of a Raney nickel catalyst is the lowest ($18.5/ kg of catalyst) among other hydrogenation catalysts.[54] The catalytic hydrogenation of xylose is known to be advantageous over the fermentative methods due to high conversion efficiency of xylose and lesser production of degradation products. This excludes the requirement for sterilization and purification steps.[54] The cost of the metal catalyst has been included in the operating costs since this can be recycled back for several cycles.

Valorization of Cellulose Content: Production of Bioethanol. The cellulosic residue left after the acid/alkaline pretreatment of pineapple processing waste is utilized for the production of ethanol by sequential enzymatic hydrolysis and fermentation.[55] The recovered cellulose is broken into glucose monomers by using the enzyme cellulase. The intermediate step involves the formation of cellobiose and other gluco-

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oligomers, which eventually get converted into glucose monomers. The enzymatic hydrolysis of cellulose is initiated at an elevated temperature (48 °C) when the enzymatic activity is the highest. Based on studies by NREL, the cellulase loading is assumed to be 20 mg enzyme (protein) per g of cellulose to achieve a conversion efficiency of 90% at a residence time of 84 h.[55] The initial solids (cellulose) loading is fixed at 20 wt % total solids. Temperature is an important parameter during the enzymatic hydrolysis step and is controlled with a pump-around loop that comprises of a centrifugal pump and a heat exchanger in the hydrolysis reactor.[55] After the enzymatic hydrolysis, the saccharified slurry is cooled to 32 °C. The hydrolyzed slurry is then inoculated with the fermenting yeast *Saccharomyces cerevisae*. The initial level of fermentation solids was maintained at 19.8% w/w of total solids and an inoculum level of 10 vol %.[55] Ethanol (5.4 wr %) present in the fermentation broth is collected in the beer well, which is designed for a residence time of 4 h to provide surge capacity between fermentation and distillation.[55] Ethanol (purity of 95%) is recovered from the fermentation beer with distillation and molecular sieve adsorption. Distillation is performed in two columns, namely, the beer column and the rectification column. Dissolved carbon dioxide and most of the water gets removed through the beer column while ethanol gets concentrated to a near-azeotropic composition through the rectification column.[55]

Valorization of the Remaining Residue: Production of Silage. The pineapple residues particularly crown is collected from the pineapple processing industries for free and hence do not contribute to the cost of raw materials required for the biorefinery. The proposed biorefinery does not deal with the crown waste for the production of biochemicals due to the high lignin content in them, which would require harsher pre-treatment conditions and would affect the overall plant economics. The residual pineapple waste left after recovery of bromelain and production of ethanol, xylitol, or XOS, is also utilized in preparing silage. The method for preparation of silage is adapted from the literature and the cost of equipment is estimated accordingly.[56−58] As per the literature, in order to prepare high-quality silage, the biomass is ensiled for 30 days in silos to maintain anaerobic conditions.

Economic Analysis

The economic analysis was conducted based upon different factors, which are given as follows:

Capital Investment Cost. The economic assessment carried out in the present study particularly estimates the net present value (NPV) and internal rate of return (IRR). The capital investment costs are estimated by calculating the total purchased cost of all the equipment and biorefinery machinery (Table 2). The equipment cost for the upstream was adapted from the NREL study[55] and previously published work.[13,59] An Aspen Plus economic analyzer was employed to estimate the downstream equipment costs. For equipment with varying capacities, the cost was adjusted according to standard engineering scaling factors[60−62]

$$(\text{new cost}) = (\text{base cost}) \times \left(\frac{\text{new size}}{\text{base size}}\right)^{0.6}$$

Energy and mass balance data was used for determining the variable operational costs. The currency used for the entire economic assessment is US dollars, adjusted to the year 2020.[63] The direct fixed capital cost (DFC) comprises of the sum of total plant direct cost (TPDC), total plant indirect cost (TPIC), and the costs related to contractor's fee and contingency. The TPDC is calculated based on the total equipment purchase cost (EPC). The plant has a lifetime of 15 years with no salvage value thereafter. The other economic evaluation parameters are given in Table 3. The annual depreciation cost is calculated by the modified accelerated cost recovery system (MACRS) for the shortest recovery period and the largest tax deductions.[64−66]

Table 3. Economic Evaluation Parameters for a Biorefinery Model Based on Pineapple Processing Waste

parameter	value
analysis year	2020
project life (years)	15
operating time (days)	300
salvage value	0
income tax (%)	28
depreciation method	MACRS[a]
discount rate (%)	10
depreciation period (years)	7
annual depreciation (%)	10
construction plan	**value**
1st year (% DFC)	30
2nd year (% DFC)	40
3rd year (% DFC)	30

[a]Modified accelerated cost recovery system.

Total Operating Cost. The total operating cost comprises raw materials, operating labor, manufacturing-cum-repair cost, contingencies, laboratory charges, plant overhead costs, utilities, administrative costs, distribution, and marketing costs. The unit costs associated with the raw materials and utilities are reported in Tables 4 and 5, respectively. The raw material cost was obtained from the literature, industries, and the market price observed in 2020 in the Indian context.

Currently, there has been no prescribed pricing for the pineapple processing wastes and these are solely thrown away in dumping yards or burnt away on fields.[18] The procurement price of pineapple waste was assumed to be similar to that of mango processing waste, which was \$25 per ton of waste.[13] Among the utility cost, electricity tariff was assumed to be \$0.15/kWh while the utility cost of cooling water and steam was estimated to be \$0.067/MT and \$17.00/MT, respectively.

Product Values and Profitability Analysis. The profitability was analyzed by calculating the revenues obtained from the final biorefinery products. The selling price of the biorefinery products (xylitol, XOS, bromelain, ethanol, and silage) was adapted from previous studies and bulk suppliers.[13,67−70] The quantity of products leaving the biorefinery at the industrial scale was calculated by scaling-up the laboratory results with the assumption of obtaining same performance under similar process conditions.[71] The profitability analysis of the biorefinery was accomplished on the basis of NPV and IRR for the initial capital investment considering the operating costs and annual cash flow over a plant life of 15 years. Comprehensive sensitivity analysis was performed to assess the most significant parameter that affects the plant economics.

Sensitivity Analysis. The fundamental goal of the current pineapple processing waste biorefinery is to valorize this waste by generating multiple products with the lowest cost of

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Table 4. Material Costs for Scenarios 1−7 in Pineapple Processing Waste Biorefinery (Base Case: 10 MTPH)[a]

		annual cost (USD)						
raw materials	unit cost (USD)	scenario 1	scenario 2	scenario 3	scenario 4	scenario 5	scenario 6	scenario 7
pineapple waste	25.0/MT	936,000	936,000	936,000	936,000	936,000	936,000	936,000
ethanol	0.6/L	13,185	13,185	16,841	1225	17,975	14,410	14,410
water	0.7/MT	77,430	80,369	157,767	2439	184,404	89,082	79,869
hydrogen	6.5/kg	187,200					187,200	187,200
nitric acid	0.64/L	520,704	571,486				520,704	520,704
sodium acetate	0.53/kg		13,356	520,273		533,629	13,356	
acetic acid	506/MT		6652	140,883		147,535	6652	
glacial acetic acid	0.49/L			215,280		215,280		
cellulase (Enzyme)	2.65/kg		111,599			111,599	111,599	
yeast	7.06/kg		1583			1583	1583	
cyclohexane	1500/MT		484			484	484	
sodium hydroxide	383.84/MT			281		281		
activated carbon	5.00/kg			2007		2007		
xylanase (enzyme)	0.176/kg			271		271		
disodium hydrogen phosphate	0.6/kg				16,373	16,373	16,373	16,373
sodium dihydrogen phosphate	0.6/kg				6165	6165	6165	6165
total cost		1,734,519	1,734,714	1,989,603	962,202	2,173,586	1,903,608	1,760,721

[a]MT means metric tons; unit costs listed are for the base case; however, variations in market prices are also considered in the later sensitivity analysis.

Table 5. Summary of Utility Cost for Base Case (10 MTPH)

		annual cost (USD)						
utility	unit cost (USD)	scenario 1	scenario 2	scenario 3	scenario 4	scenario 5	scenario 6	scenario 7
electricity	0.15 /kW-h	178,846	56,506	254,525	60,767	315,292	239,605	239,605
steam	17.00/MT	134,640	166,839	1,704,709	1630	1,672,694	146,322	136,270
cooling water	0.067/MT			494,460	3394	497,854	3394	3394
total		313,486	223,345	2,453,694	65,791	2,485,840	389,321	379,269

Table 6. Annual Operating Costs for Pineapple Processing Waste Biorefinery (Base Case: 10 MTPH)

	cost (USD)						
item	scenario 1	scenario 2	scenario 3	scenario 4	scenario 5	scenario 6	scenario 7
raw materials	1,734,519	1,734,714	1,989,603	962,202	2,173,586	1,903,608	1,760,721
operating labor	519,000	519,000	596,881	288,661	652,103	571,082	528,216
manufacturing and repairs	242,200	242,200	278,544	134,708	304,314	266,505	246,501
contingencies	103,800	103,800	119,376	57,732	130,420	114,216	105,643
lab charges	77,850	77,850	89,532	43,299	97,815	85,662	79,232
fixed charges	519,000	519,000	596,881	288,660	652,103	571,082	528,216
plant overhead cost	311,400	311,400	358,128	173,196	391,261	342,649	316,929
administrative	129,750	129,750	149,220	72,165	163,025	142,770	132,054
distribution and marketing cost	173,000	173,000	198,960	96,220	217,367	190,360	176,072
utilities	313,486	223,345	2,453,694	65,791	2,485,840	389,321	379,269
total	4,262,405	4,172,459	6,950,195	2,182,634	7,441,727	4,729,543	4,393,710

production. Variability in factors such as the capacity of the plant, the number of days when the plant operates, and such others are expected to directly affect the overall plant economics. Parameters such as tax rate and the cost of raw materials affect the economic feasibility of the processing unit. Sensitivity analysis was conducted by calculating the NPV of each of the scenarios after varying one parameter while keeping the others constant. The sensitivity of results was presented by constructing tornado charts for the baseline scenario and the accompanying variable sensitivities. In the present study, the parameters considered are (i) plant capacity (5, 10, 20 MTPH); (ii) days of operation per year (270, 300, 330 days); (iii) plant lifetime (12, 15, 18 years); (iv) income tax (23%, 28%, 33%); (v) cost of raw material ($10, $25, $40); and (vi) selling price of product (base case ± 25%).

RESULTS AND DISCUSSION

Fixed Capital Cost of Biorefinery

The direct fixed capital cost (DFC) for different scenarios were calculated in the range from $1.5 million to $39.3 million (Table 2). The purchase and installation of reactor tank, extractor unit, centrifuges, and precipitator tanks were among the major contributors to the total plant direct cost. The lowest DFC, i.e., $1.5 million, was estimated for scenario 4 for the production of bromelain and silage. The production of more than two products (as in the case of scenarios 5, 6, and 7)

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Table 7. Summary of the Revenue Generated from the Products in Different Scenarios for a Plant Capacity of 10 MTPH

		revenue (USD)						
products	selling price (USD)	scenario 1	scenario 2	scenario 3	scenario 4	scenario 5	scenario 6	scenario 7
bromelain	8600/MT				136,534	136,534	136,534	136,534
XOS	4000/MT			1,928,400		1,928,400		
xylitol	4000/MT	7,680,000					7,680,000	7,680,000
ethanol	0.59/L		633,632			633,632	633,632	
silage	40/MT	458,628	456,828	458,628	1,607,400	374,400	374,400	458,628
total revenue		8,138,628	1,090,460	2,387,028	1,743,934	3,072,966	8,824,566	8,275,162

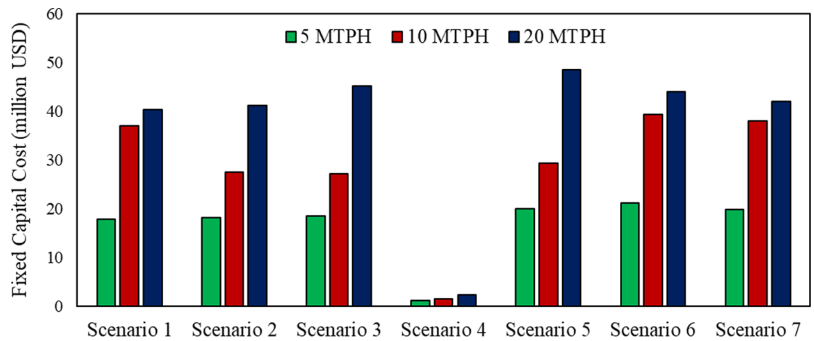

Figure 3. Variation in the fixed capital cost (FCC) of the scenarios[1−7] at different plant capacities.

often led to a higher DFC, which could be attributed to a greater number of processes involved. In scenario 5, the DFC was estimated to be \$29.3 million, which is less when compared to scenarios 6 and 7 for which the DFC was estimated as \$39.3 million and \$37.9 million respectively.

Operating Cost

The breakdown of annual operating costs for all the scenarios is illustrated in Table 6. The raw materials accounted for about 28 to 42% of the annual operating costs. The share of utility cost varied from 5.3 to 35.3% in the annual operating costs. The annual operating cost for scenario 6 was estimated to be \$7.4 million, which is the highest among all the scenarios. It could be attributed to the cost associated with the production of XOS as one of the products in the biorefinery since the annual operating cost for individual production of XOS (scenario 3) was estimated to be \$6.9 million, which is quite large for a single product.

Profitability Analysis

The economic performance of all the scenarios was evaluated in terms of NPV and IRR. A significant revenue boost was obtained for the scenarios with the generation of multiple products (Table 7). Scenario 6 generated maximum annual revenue of \$8.8 million for a base case of 10 MTPH. Variables such as plant capacity have a significant effect on the profitability of a biorefinery scenario. So, the capital investment for all the scenarios was compared for different plant capacities (Figure 3). The effect of such variables on the NPV of different scenarios was evaluated as a part of the sensitivity analysis.

Sensitivity Analysis

The plant capacity and selling price of products are among the variables that significantly affect plant economics in most of the scenarios. Income tax had insignificant effect on plant economics in all the scenarios. The effect of these parameters on plant economics is discussed for each of the scenarios considered in this study.

Scenario 1. The selling price of the final product, which is xylitol for scenario 1, is the most influential parameter (Figure 4a). The base case price for xylitol was \$4 per kg, which is quite acceptable when compared to the global market. The lower bound on the selling price of xylitol was assumed to be \$3 per kg, and the highest selling price was assumed to be \$5 per kg for carrying out the sensitivity analysis. Increasing the selling price of the products made this venture profitably feasible (NPV > 0). The increment in NPV was 104% compared with the base case with an IRR of 10%. Plant capacity is the second most dominating factor that influences plant economics. A two-fold increase (from 10 MTPH to 20 MTPH) in the plant capacity resulted in only a 9% increase in FCC. However, the increment in NVP for 20 MTPH was 175% in comparison to base case, making this venture economically feasible (NPV > 0) with an IRR of 14%.

Scenario 2 and 3. Plant capacity was the most influential parameter for both scenarios 2 and 3 (Figure 4b,c). However, with the given parameters, the venture was not profitable because the revenue generated by ethanol alone (scenario 2) is not very significant when compared to the annual operating cost and the initial investment required. Similarly, the production of XOS alone is not a profitable venture (NPV < 0).

Scenario 4. As depicted in Figure 4d, the economics of scenario 4 is significantly influenced by the cost of raw materials. A decrease in the price for procurement of pineapple waste from \$25/ton to \$10/ton made this venture profitable with an NPV of \$3.3 million and IRR of 42%.

Scenario 5. The plant capacity is the most influential parameter for scenario 5 (Figure 4e). The parameters are taken into consideration still could not make this venture profitable mainly because of the high cost of production of XOS and lower revenue generation for ethanol, which are the biorefinery products in this scenario.

Scenario 6. As depicted in Figure 4f, the selling price of the products is the most influential parameter. The increase in the selling price of biorefinery products such as xylitol (from \$4/kg

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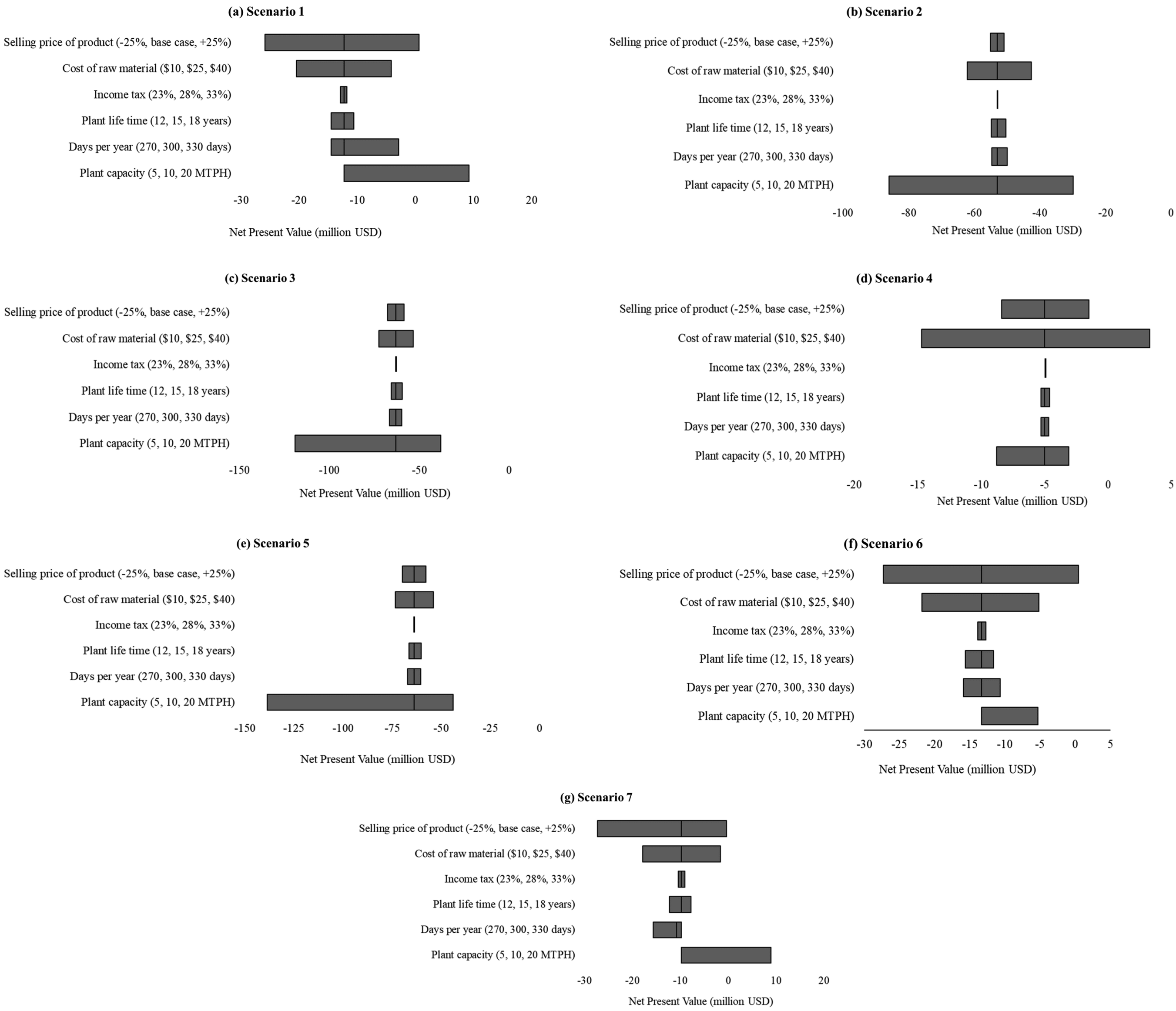

Figure 4. Sensitivity of the net present value to different parameters for (a) scenario 1, (b) scenario 2, (c) scenario 3, (d) scenario 4, (e) scenario 5, (f) scenario 6, and (g) scenario 7.

to \$5/kg), ethanol (\$0.59/L to \$0.74/L), and bromelain (\$8.6/kg to \$10.7/kg) incremented the net present value by 103% with an IRR of 10%. Hence, on increasing the selling price of the products by 25%, the venture was converted into a profitable business (NPV > 0).

Scenario 7. This scenario represents the production of two main products namely, bromelain and xylitol. As depicted in Figure 4g, the selling price of the products is the most influential parameter. On increasing the selling price of the products by 25% of the base case, the net present value increased by 96%; however, the venture remains unprofitable (NPV < 0). Plant capacity is another parameter that influenced the economics of scenario 7. On increasing the plant capacity by two folds (20 MTPH), the venture was converted into a profitable one (NPV > 0). The net present value got an increment of 190% and an IRR of 14%.

CONCLUSION AND FUTURE PROSPECTS

In this work, a techno-economic model was developed for pineapple processing waste biorefinery with a base capacity of 10 MTPH. Different scenarios (with dual or multiple products) were analyzed for their economic feasibility. For an economically feasible venture, it is ideal that the total capital investment is the minimum with maximum revenue returns. According to the sensitivity analysis, the plant capacity and selling price of finished products had a substantial impact on plant economics. The plant capacities larger than the base capacity often made the venture economically feasible as in the case of scenarios 1 and 7. On increasing the selling price of the products by 25% of the base case, scenarios 1 and 6 became economically viable (NPV > 0). A decrease in the price for procurement of pineapple waste from \$25/ton to \$10/ton made scenario 4 profitable with an NPV of \$3.3 million and IRR of 42%. The number of operating days is another parameter that affects plant economics. In the present analysis, the plant is assumed to be running to its maximum capacity for 300 days. The continuous supply of raw material is taken care of by storing it for four additional months. The cost associated with the storage is included in the total cost of pineapple processing waste. To maintain a constant supply of biomass, it is worth considering multiple feedstocks for running this plant. Most of the products such as xylitol, bioethanol, and XOS could be obtained from other lignocellulosic residues as well. The pineapple processing waste could be combined with the pineapple leaves and stem (on-farm waste) to achieve an economy of scale. The overall analysis shows that pineapple processing waste, which is currently being dumped into landfills or burnt away in some places, could be utilized as an excellent bioresource for recovering/producing value-added compounds such as bromelain and xylitol. Further, multi-feedstocks such as corn cob, mango processing waste, citrus processing waste, pomegranate processing waste, and wastes from processing of other seasonal fruits could be integrated with pineapple processing waste to operate a large-scale facility to make the venture profitable.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsengineeringau.1c00028.

Description of proportion of pineapple processing wastes (crown, peels, core, and pomace); summaries of estimation of total equipment cost for scenarios 1 to 7; Aspen process flowsheet for xylitol production from xylose fraction; and Aspen process flowsheet for the recovery of ethanol using distillation (PDF)

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Notes

The authors declare no competing financial interest.

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REFERENCES

(1) Lokesh, K.; Ladu, L.; Summerton, L. Bridging the gaps for a "circular" bioeconomy: Selection criteria, bio-based value chain and stakeholder mapping. *Sustainable* **2018**, *10*, 1695.

(2) Cherubini, F. The biorefinery concept: Using biomass instead of oil for producing energy and chemicals. *Energy Convers. Manage.* **2010**, *51*, 1412−1421.

(3) Meghana, M.; Shastri, Y. Sustainable valorization of sugar industry waste: Status, opportunities, and challenges. *Bioresour. Technol.* **2020**, *303*, 122929.

(4) Caldeira, C.; Vlysidis, A.; Fiore, G.; De Laurentiis, V.; Vignali, G.; Sala, S. Sustainability of food waste biorefinery: A review on valorisation pathways, techno-economic constraints, and environmental assessment. *Bioresour. Technol.* **2020**, *312*, 123575.

(5) Nizami, A. S.; Rehan, M.; Waqas, M.; Naqvi, M.; Ouda, O. K. M.; Shahzad, K.; et al. Waste biorefineries: Enabling circular economies in developing countries. *Bioresour. Technol.* **2017**, *241*, 1101−1117.

(6) Ren, Y.; Yu, M.; Wu, C.; Wang, Q.; Gao, M.; Huang, Q.; et al. A comprehensive review on food waste anaerobic digestion: Research updates and tendencies. *Bioresour. Technol.* **2018**, *247*, 1069−1076.

(7) Tsagkari, M.; Couturier, J. L.; Kokossis, A.; Dubois, J. L. Early-Stage Capital Cost Estimation of Biorefinery Processes: A Comparative Study of Heuristic Techniques. *ChemSusChem* **2016**, *9*, 2284−2297.

(8) Rajesh Banu, J.; Preethi, K. S.; Gunasekaran, M.; Kumar, G. Microalgae based biorefinery promoting circular bioeconomy-techno economic and life-cycle analysis. *Bioresour. Technol.* **2020**, *302*, 122822.

(9) Li, X.; Mupondwa, E.; Tabil, L. Technoeconomic analysis of biojet fuel production from camelina at commercial scale: Case of Canadian Prairies. *Bioresour. Technol.* **2018**, *249*, 196−205.

(10) Dávila, J. A.; Rosenberg, M.; Cardona, C. A. Techno-economic and Environmental Assessment of p-Cymene and Pectin Production from Orange Peel. *Waste Biomass Valoriz.* **2015**, *6*, 253−261.

(11) Lohrasbi, M.; Pourbafrani, M.; Niklasson, C.; Taherzadeh, M. J. Process design and economic analysis of a citrus waste biorefinery with biofuels and limonene as products. *Bioresour. Technol.* **2010**, *101*, 7382−7388.

(12) Hernández, V.; Romero-García, J. M.; Dávila, J. A.; Castro, E.; Cardona, C. A. Techno-economic and environmental assessment of an olive stone based biorefinery. *Resour. Conserv. Recycl.* **2014**, *92*, 145−150.

(13) Arora, A.; Banerjee, J.; Vijayaraghavan, R.; MacFarlane, D.; Patti, A. F. Process design and techno-economic analysis of an integrated mango processing waste biorefinery. *Ind. Crops Prod.* **2018**, *116*, 24−34.

(14) Dávila, J. A.; Rosenberg, M.; Cardona, C. A. A biorefinery for efficient processing and utilization of spent pulp of Colombian Andes Berry (Rubus glaucus Benth.): Experimental, techno-economic and environmental assessment. *Bioresour. Technol.* **2017**, *223*, 227−236.

(15) Altendorf, S. Major Tropical Fruits Market Review 2018; FAO: Rome; 2019.

(16) APEDA. *Indian Production of Pineapple [Internet]. National Horticulture Board.* 2018 [cited 2021 May 25]. Available from: http://agriexchange.apeda.gov.in/IndiaProduction/India_Productions.aspx?cat=fruit&hscode=1056

(17) HortInnovation. *Australian Horticulture Satistics Handbook - Fruits [Internet]. Sydney*; 2018 [cited 2021 May 25]. Available from: https://www.horticulture.com.au/growers/help-your-business-grow/research-reports-publications-fact-sheets-and-more/HA18002/

https://doi.org/10.1021/acsengineeringau.1c00028
ACS Eng. Au 2022, 2, 208−218

(18) Banerjee, S.; Ranganathan, V.; Patti, A.; Arora, A. Valorisation of pineapple wastes for food and therapeutic applications. *Trends Food Sci. Technol.* **2018**, *82*, 60−70.

(19) Ketnawa, S.; Chaiwut, P.; Rawdkuen, S. Pineapple wastes: A potential source for bromelain extraction. *Food Bioprod. Process.* **2012**, *90*, 385−391.

(20) Gil, L. S.; Maupoey, P. F. An integrated approach for pineapple waste valorisation. Bioethanol production and bromelain extraction from pineapple residues. *J. Cleaner Prod.* **2018**, *172*, 1224−1231.

(21) Khedkar, M. A.; Nimbalkar, P. R.; Gaikwad, S. G.; Chavan, P. V.; Bankar, S. B. Sustainable biobutanol production from pineapple waste by using Clostridium acetobutylicum B 527: Drying kinetics study. *Bioresour. Technol.* **2017**, *225*, 359−366.

(22) Pineapple, V. T.. In: Galanakis, C. M., editor. *Valorization of Fruit Processing By-products*. 1st ed. Elsevier: 2020. p. 203−26.

(23) Banerjee, S.; Patti, A. F.; Ranganathan, V.; Arora, A. Hemicellulose based biorefinery from pineapple peel waste: Xylan extraction and its conversion into xylooligosaccharides. *Food Bioprod. Process.* **2019**, *117*, 38−50.

(24) Jusoh, N.; Othman, N.; Idris, A.; Nasruddin, A. Characterization of liquid pineapple waste as carbon source for production of succinic acid. *J. Teknol.* **2014**, *69*, 11−13.

(25) Ueno, T.; Ozawa, Y.; Ishikawa, M.; Nakanishi, K.; Kimura, T. Lactic acid production using two food processing wastes, canned pineapple syrup and grape invertase, as substrate and enzyme. *Biotechnol. Lett.* **2003**, *25*, 573−577.

(26) Sukruansuwan, V.; Napathorn, S. C. Use of agro-industrial residue from the canned pineapple industry for polyhydroxybutyrate production by Cupriavidus necator strain A-04. *Biotechnol. Biofuels.* **2018**, *11*, 202.

(27) Banerjee, S.; Ranganathan, V.; Arora, A.; Patti, A. F. Green approach towards hydrolysing wheat gluten using waste ingredients from pineapple processing industries. *Int. J. Food Sci. Technol.* **2021**, *56*, 1724−1733.

(28) Banerjee, S.; Vijayaraghavan, R.; Patti, A. F.; Arora, A. Integrated Biorefinery Strategy for Valorization of Pineapple Processing Waste into High-Value Products. *Waste Biomass Valoriz.* **2022**, 631.

(29) Banerjee, S.; Arora, A.; Vijayaraghavan, R.; Patti, A. F. Extraction and crosslinking of bromelain aggregates for improved stability and reusability from pineapple processing waste. *Int. J. Biol. Macromol.* **2020**, *158*, 318−326.

(30) Pradhan, P.; Gadkari, P.; Mahajani, S. M.; Arora, A. A conceptual framework and techno-economic analysis of a pelletization-gasification based bioenergy system. *Appl. Energy.* **2019**, *249*, 1−13.

(31) Campos, D. A.; Ribeiro, T. B.; Teixeira, J. A.; Pastrana, L.; Pintado, M. M. Integral valorization of pineapple (Ananas comosus L.) By-products through a green chemistry approach towards Added Value Ingredients. *Foods* **2020**, *9*, 60.

(32) Azizan, A.; Lee, A. X.; Hamid, N. A. A.; Maulidiani, M.; Mediani, A.; Ghafar, S. Z. A.; et al. Potentially bioactive metabolites from pineapple waste extracts and their antioxidant and α-glucosidase inhibitory activities by 1H NMR. *Foods.* **2020**, *9*, 173.

(33) Prado, K. S.; Spinacé, M. A. S. Isolation and characterization of cellulose nanocrystals from pineapple crown waste and their potential uses. *Int. J. Biol. Macromol.* **2019**, *122*, 410−416.

(34) Casabar, J. T.; Unpaprom, Y.; Ramaraj, R. Fermentation of pineapple fruit peel wastes for bioethanol production. *Biomass. Convers. Biorefin.* **2019**, *9*, 761−765.

(35) Khedkar, M. A.; Nimbalkar, P. R.; Kamble, S. P.; Gaikwad, S. G.; Chavan, P. V.; Bankar, S. B. Process intensification strategies for enhanced holocellulose solubilization: Beneficiation of pineapple peel waste for cleaner butanol production. *J. Cleaner Prod.* **2018**, *199*, 937−947.

(36) Sepúlveda, L.; Romaní, A.; Aguilar, C. N.; Teixeira, J. Valorization of pineapple waste for the extraction of bioactive compounds and glycosides using autohydrolysis. *Innov. Food Sci. Emerg. Technol.* **2018**, *47*, 38−45.

(37) Choonut, A.; Saejong, M.; Sangkharak, K. The production of ethanol and hydrogen from pineapple peel by Saccharomyces cerevisiae and Enterobacter aerogenes. *Energy Procedia.* **2014**, *52*, 242−249.

(38) Bernardes, T. F.; Daniel, J. L. P.; Adesogan, A. T.; McAllister, T. A.; Drouin, P.; Nussio, L. G.; Huhtanen, P.; Tremblay, G. F.; Bélanger, G.; Cai, Y. Silage review: Unique challenges of silages made in hot and cold regions. *J. Dairy Sci.* **2018**, *101*, 4001−4019.

(39) Borreani, G.; Tabacco, E.; Schmidt, R. J.; Holmes, B. J.; Muck, R. E. Silage review: Factors affecting dry matter and quality losses in silages. *J. Dairy Sci.* **2018**, *101*, 3952−3979.

(40) Soares, P. A. G.; Vaz, A. F. M.; Correia, M. T. S.; Pessoa, A.; Carneiro-Da-Cunha, M. G. Purification of bromelain from pineapple wastes by ethanol precipitation. *Sep. Purif. Technol.* **2012**, *98*, 389−395.

(41) Barreto, J. C.; Trevisan, M. T. S.; Hull, W. E.; Erben, G.; De Brito, E. S.; Pfundstein, B.; Würtele, G.; Spiegelhalder, B.; Owen, R. W. Characterization and quantitation of polyphenolic compounds in bark, kernel, leaves, and peel of mango (Mangifera indica L.). *J. Agric. Food Chem.* **2008**, *56*, 5599−5610.

(42) Geng, W.; Narron, R.; Jiang, X.; Pawlak, J. J.; Chang, H.; Park, S.; Jameel, H.; Venditti, R. A. The influence of lignin content and structure on hemicellulose alkaline extraction for non-wood and hardwood lignocellulosic biomass. *Cellulose* **2019**, *26*, 3219−3230.

(43) Wei, L.; Yan, T.; Wu, Y.; Chen, H.; Zhang, B. Optimization of alkaline extraction of hemicellulose from sweet sorghum bagasse and its direct application for the production of acidic xylooligosaccharides by Bacillus subtilis strain MR44. *PLoS One* **2018**, *13*, No. e0195616.

(44) Oriez, V.; Peydecastaing, J.; Pontalier, P.-Y. Lignocellulosic Biomass Mild Alkaline Fractionation and Resulting Extract Purification Processes: Conditions, Yields, and Purities. *Clean Technol.* **2020**, *2*, 91−115.

(45) Júnior, D. L.; Ayoub, A.; Venditti, R. A.; Jameel, H.; Colodette, J. L.; Chang, H. Ethanol precipitation of hetero-polysaccharide material from hardwood by alkaline extraction prior to the kraft cooking process. *BioResources* **2013**, *8*, 5319−5332.

(46) Khat-udomkiri, N.; Sivamaruthi, B. S.; Sirilun, S.; Lailerd, N.; Peerajan, S.; Chaiyasut, C. Optimization of alkaline pretreatment and enzymatic hydrolysis for the extraction of xylooligosaccharide from rice husk. *AMB Express.* **2018**, *8*, 115.

(47) Azelee, N. I. W.; Jahim, J. M.; Ismail, A. F.; Fuzi, S. F. Z. M.; Rahman, R. A.; Illias, R. M. High xylooligosaccharides (XOS) production from pretreated kenaf stem by enzyme mixture hydrolysis. *Ind. Crops Prod.* **2016**, *81*, 11−19.

(48) Samanta, A. K.; Jayapal, N.; Kolte, A. P.; Senani, S.; Sridhar, M.; Dhali, A.; et al. Process for Enzymatic Production of Xylooligosaccharides from the Xylan of Corn Cobs. *J. Food Process Preserv.* **2015**, *39*, 729−736.

(49) Santana, N. B.; Dias, J. C. T.; Rezende, R. P.; Franco, M.; Oliveira, L. K. S.; Souza, L. O. Production of xylitol and biodetoxification of cocoa pod husk hemicellulose hydrolysate by Candida boidinii XM02G. *PLoS One* **2018**, *13*, No. e0195206.

(50) Xia, H.; Zhang, L.; Hu, H.; Zuo, S.; Yang, L. Efficient hydrogenation of xylose and hemicellulosic hydrolysate to xylitol over Ni-Re bimetallic nanoparticle catalyst. *Nanomaterials* **2020**, *10* (), DOI: 10.3390/nano10010073.

(51) Ribeiro, L. S.; Delgado, J. J.; De Melo Órfão, J. J.; Ribeiro Pereira, M. F. A one-pot method for the enhanced production of xylitol directly from hemicellulose (corncob xylan). *RSC Adv.* **2016**, *6*, 95320−95327.

(52) Baudel, H. M.; de Abreu, C. A. M.; Zaror, C. Z. Xylitol production via catalytic hydrogenation of sugarcane bagasse dissolving pulp liquid effluents over Ru/C catalyst. *J. Chem. Technol. Biotechnol.* **2005**, *80*, 230−233.

(53) Mikkola, J. P.; Salmi, T.; Sjöholm, R. Modelling of kinetics and mass transfer in the hydrogenation of xylose over Raney nickel catalyst. *J. Chem. Technol. Biotechnol.* **1999**, *74*, 655−662.

(54) Özüdoğru, H. M. R.; Nieder-Heitmann, M.; Haigh, K. F.; Görgens, J. F. Techno-economic analysis of product biorefineries

utilizing sugarcane lignocelluloses: Xylitol, citric acid and glutamic acid scenarios annexed to sugar mills with electricity co-production. *Ind. Crops Prod.* **2019**, *133*, 259−268.
(55) Humbird, D.; Davis, R.; Tao, L.; Kinchin, C.; Hsu, D.; Aden, A.; Schoen, P.; Lukas, J.; Olthof, B.; Worley, M.; Sexton, D.; Dudgeon, D. Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol: Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover. *Natl. Renew. Energy Lab.* **2011**, DOI: 10.2172/1013269.
(56) Buliah, N.; Jamek, S.; Ajit, A.; Abu, R. Production of dairy cow pellets from pineapple leaf waste. In: *AIP Conference Proceedings*; AIP Publishing LLC 2019.
(57) Suphalucksana, W.; Sangsoponjit, S.; Srikijkasemwat, K. Using leucaena to improve the quality of pineapple plant silage. *Chem. Eng. Trans.* **2017**, *58*, 847−852.
(58) Gowda, N. K. S.; Vallesha, N. C.; Awachat, V. B.; Anandan, S.; Pal, D. T.; Prasad, C. S. Study on evaluation of silage from pineapple (Ananas comosus) fruit residue as livestock feed. *Trop. Anim. Health Prod.* **2015**, *47*, 557−561.
(59) Arora, A.; Singh, V. Biodiesel production from engineered sugarcane lipids under uncertain feedstock compositions: Process design and techno-economic analysis. *Appl Energy.* **2020**, *280*, 115933.
(60) Gallagher, P. W.; Brubaker, H.; Shapouri, H. Plant size: Capital cost relationships in the dry mill ethanol industry. *Biomass Bioenergy* **2005**, *28*, 565−571.
(61) ul Alam, W.; Amos, J. M. The economies of scale of fuel-grade ethanol plants. *Energy* **1982**, *7*, 477−481.
(62) Aui, A.; Wang, Y.; Mba-Wright, M. Evaluating the economic feasibility of cellulosic ethanol: A meta-analysis of techno-economic analysis studies. *Renewable Sustainable Energy Rev.* **2021**, *145*, 111098.
(63) CostIndex. Chemical Engineering Magazine Plant Cost Index. *Plant Cost Index.* **2018**, 1−118.
(64) Kazi, F. K.; Fortman, J. A.; Anex, R. P.; Hsu, D. D.; Aden, A.; Dutta, A.; et al. Techno-economic comparison of process technologies for biochemical ethanol production from corn stover. *Fuel* **2010**, *89*, S20−S28.
(65) Na, J.; Seo, B.; Kim, J.; Lee, C. W.; Lee, H.; Hwang, Y. J.; et al. General technoeconomic analysis for electrochemical coproduction coupling carbon dioxide reduction with organic oxidation. *Nat. Commun.* **2019**, *10*, 5193.
(66) Pookpunt, S.; Ongsakul, W.; Madhu, N. A comprehensive techno-economic analysis for optimally placed wind farms. *Electr Eng.* **2020**, *102*, 2161−2179.
(67) *Bromelain Price [Internet]*. Indiamart. 2020 [cited 2021 May 25]. Available from: https://dir.indiamart.com/search.mp?ss=bromelain
(68) Rosales-Calderon, O.; Arantes, V. A review on commercial-scale high-value products that can be produced alongside cellulosic ethanol. *Biotechnol Biofuels.* **2019**, *12*, 240.
(69) Lopes, T. F.; Carvalheiro, F.; Duarte, L. C.; Gírio, F.; Quintero, J. A.; Aroca, G. Techno-economic and life-cycle assessments of small-scale biorefineries for isobutene and xylo-oligosaccharides production: a comparative study in Portugal and Chile. *Biofuels, Bioprod. Biorefin.* **2019**, *13*, 1321−1332.
(70) Ali Mandegari, M.; Farzad, S.; Görgens, J. F. Economic and environmental assessment of cellulosic ethanol production scenarios annexed to a typical sugar mill. *Bioresour. Technol.* **2017**, *224*, 314−326.
(71) Albarelli, J. Q.; Santos, D. T.; Cocero, M. J.; Meireles, M. A. A. Economic analysis of an integrated annatto seeds-sugarcane biorefinery using supercritical CO2 extraction as a first step. *Materials* **2016**, *9*, 494.

https://doi.org/10.1021/acsengineeringau.1c00028
ACS Eng. Au 2022, 2, 208−218