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Sustainable Process Design for Apple Pomace Based Biorefinery in the Agro-industry

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Biomass generated from agricultural processing residues has enormous energy potential and economic value. System analysis and design of a biorefinery using apple pomace as the main production feedstock was carried out. Three process pathways were designed (e.g., anaerobic fermentation, pyrolysis process, and value-added chemical products). A sustainability analysis for each process focused on its economic and environmental impact issues. Three pathways were modelled using Aspen Plus. The simulation results were used to determine yields and their investment feasibility and carbon footprint. Different perspectives may lead to different optimal pathways. The biorefining of apple pomace produces value-added products such as pectin, in addition to energy. These bioenergy sources can be used to replace fossil energy and are renewable, thus reducing CO_2 emissions. Solutions are also proposed for pathways that are on the disadvantageous side.

1. Introduction

The global trend in energy production is moving towards circular economic systems and sustainable resources. Renewable energy sources are an important part of meeting the growing demand for energy and mitigating climate change, despite the potential adverse effects of the technologies used to produce such energy (Gibson et al., 2017). Environmentally friendly and renewable energy sources include bio-waste, wind, solar, hydro, geothermal and hydrogen. The use of agricultural waste biomass is seen as a major alternative energy source that can significantly reduce greenhouse gas emissions. Agricultural waste generated at all stages of agricultural production is used as a sustainable biomass asset for bioenergy production. Apple pomace is rich in free sugars and structural carbohydrates, it also can prove to be a good feedstock for biofuel and value-added chemical production (Vaez et al., 2023). Similar to apple pomace, the solid biomass residues during olive oil extraction can also become an important source of renewable energy (Romaniello et al., 2024). Agro-industrial wastes and especially highlighting the by-products of sugar cane and panela production, can be used to produce sustainable aviation fuel (López et al., 2024). As a common waste, apple pomace is not fully used effectively compared with other feedstocks, so it has great potential.

Biorefineries use biomass to produce fuel, power and chemicals in facilities that combine biomass conversion technologies (Darkwah et al., 2018). The apple pomace can be integrated into a biorefinery through several processes (physical, chemical, thermochemical or biological) to effectively added value. The implementation of value-added technologies for apple residue and other agricultural product processing residues can reduce the negative environmental impact of waste as composting or waste disposal activities. As the main by-product of apple processing, apple pomace is of vital importance to improve the quality and efficiency of the whole apple industry (Ma et al., 2024). Pectin is one of the most convenient and widely used products among many value-added products. Andrzejewsk (2024) proves that forward osmosis technology can significantly improve the economic feasibility and environmental friendliness of pectin recovery. Based on hypermethylated (HM) apple pectin, glycerol and margarine can be made into fully biodegradable films, creating greater economic value (Fiedot et al., 2024). Biosuccinate produced by apple pomace fermentation is a valuable intermediate that is far more economically valuable than pectin, but lacks practical applications (González et al., 2018). Apple pomace can also be used to extract antibacterial molecules, bringing additional medical value (Bruna et al., 2024). This

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work aims to provide an idea for designing sustainable biorefinery processes. The biorefinery using apple pomace as feedstocks is studied.

2. Methodological framework

With the process simulation support, process design of sustainable utilization of apple pomace can be realized, which is conducive to the development of circular economy. Besides, it is essential to carry out technical and economic assessment as well as other assessments to determine the feasibility of the process. This work presents a general framework for the design of biorefineries with apple pomace in the agro-industry as feedstocks.

2.1 Process design of sustainable biorefineries

Scenario 1 is ***biogas production***. It was widely reported the biogas production was derived from liquid fertilizers, corn silage, fruit and vegetable wastes effectively. Methane is the main component in the biogas and regarded as a clean fuel with high economic feasibility to be exploited (Zhang et al., 2021). These crop-residue can be reused as processed waste. They can be anaerobic digestion under the right temperature (referred to as AD), and the product is biogas. AD consists of four successive stages: hydrolysis, acid production, acetone production and methane production. Biogas with a methane concentration of 50 %~65 % is generated through AD, which has low combustion efficiency. Therefore, biogas with a methane concentration of more than 95 % is generated through biogas purification process to improve combustion performance and remove excess impurities such as CO_2, H_2S and water vapor from CH_4. The specific process flow is shown in Figure 1. Only the waste raw materials such as feces and straw were studied, and not the processing residues of agricultural products were not involved. Therefore, this paper takes apple pomace as the feedstocks for production, and verifies the feasibility of the application.

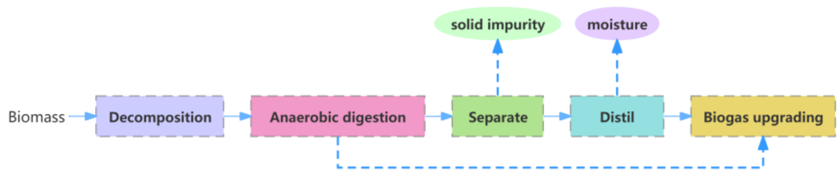

Figure 1: Flowchart of anaerobic digestion process

The upgraded biogas can be used as an alternative to natural gas for energy supply and as a feedstock for chemical synthesis. According to different separation principles, the current common biogas purification technologies are: adsorption method, high pressure water washing method (physical absorption method), chemical absorption method (amine washing method), membrane separation method, etc. After analyzing the advantages and disadvantages of each method, this paper will use high-pressure water washing method to upgrade biogas (Cozma et al., 2013).
Scenario 2 is ***pyrolysis***. Biomass is the renewable carbon source, which can produce bio-char through pyrolysis under anaerobic or hypoxic conditions. Bio-char has a rich pore structure, a large specific surface area and special adsorption properties (Liu et al., 2022). The energy extraction from the fruit wastes can be accomplished using pyrolysis, as it has been considered as one of the most effective methods of energy recovery from biomass. The pyrolysis delivers products in three forms—solid (bio-char), liquid (bio-oil), and syngas (pyrolytic gas). Three modes of pyrolysis, namely, slow, fast, and flash, are in practice. Slow pyrolysis produces more char, while fast and flash favor bio-oil and syngas generation (AlNouss et al., 2021). The most effective method of biomass valorisation from pyrolysis whilst still maintaining a simple and cost-effective setup would be in maximising the yield of bio-char and bio-oil (Zhang et al., 2017). In this design, the pyrolysis process at a temperature of 500 ℃ will be adopted, and the specific process is shown in Figure 2. This study uses grape residue as the process feedstock, and this paper innovatively uses apple pomace as a new feedstock.
Scenario 3 is ***value-added products pectin production***. Pectin is a component of the cell walls of plants that is composed of acidic sugar-containing backbones with neutral sugar-containing side chains. It functions in cell adhesion and wall hydration, and pectin crosslinking influences wall porosity and plant morphogenesis. Pectins are abundant in the waste residues of fruits and vegetables, which could be used as feedstocks for ethanol production (Xiao et al., 2013). The pectin is also a promising nutraceutical ingredient for drug delivery and formation of nanoemulsion (Kumar et al., 2020). The pectin and other value-added products process designed in this paper is based on the zero-emission bio-refining process proposed by Vukušić (2021). The specific process is shown in Figure 3.

2.2 Sustainability analysis

Sustainability is defined as the balance between economic, environmental and social issues. By implementing new technologies, biomass is used as a renewable feedstock instead of crude oil. In this sense, biorefinery is by definition sustainable (Solarte-Toro et al., 2023). Many studies only quantitatively assess sustainability from environmental, economic and comprehensive perspectives, and have not involved analysis of the social dimension. Techno-economic analysis is an important part for process design. Labor costs are included in the economic analysis. The number of direct employees (NDE) is suitable for social analysis. This part has been calculated in the economic analysis. Thus, social analysis is not conducted separately. The calculation of the total costs shall include the operating costs. The formula for the calculation of the TOC of the total operating costs is shown in Eq. (1), where the total labor cost TLC of the system includes labor-related calculations. Environmental impact was performed in terms of greenhouse gas emissions given as a CO_2 equivalence (CO_2e). The economic assessment is partly based on the method used by Jalili et al. (2024). The cost of each equipment is calculated by Eqs. (2)-(3) (Scholz et al., 2013). Eq. (2) is used for compressors, heat exchangers, and pumps, where S represents the size of the equipment. For the absorber and pressure vessel, the height l and the diameter d determine the investment cost, which is calculated by Eq. (3). In Eq. (4), the net present value (NPV) is used to judge the economic situation of biorefineries (Xing et al., 2020; Okoro et al., 2023).

$$\mathrm{TOC} = 1.25(\mathrm{TFC} + \mathrm{R_m}) + 2.7\mathrm{TLC} + 0.2\mathrm{FCI} \tag{1}$$

$$\mathrm{BC} = \mathrm{C_0}\left(\frac{\mathrm{S}}{\mathrm{S_0}}\right)^{\alpha} \tag{2}$$

$$\mathrm{BC} = \left(\frac{\mathrm{l}}{\mathrm{l_0}}\right)^{\alpha}\left(\frac{\mathrm{d}}{\mathrm{d_0}}\right)^{\beta} \tag{3}$$

$$NPV = \sum_{t=1}^{n} \frac{CF}{(1+i)^t} - C_0 \tag{4}$$

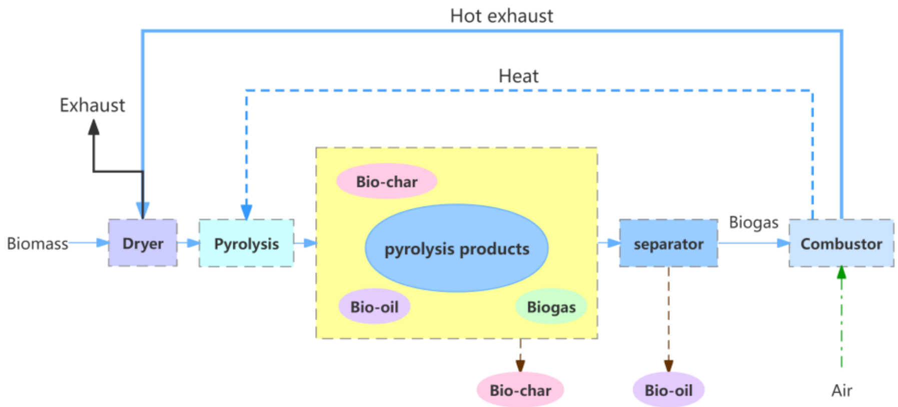

Figure 2: Flowchart of pyrolysis process

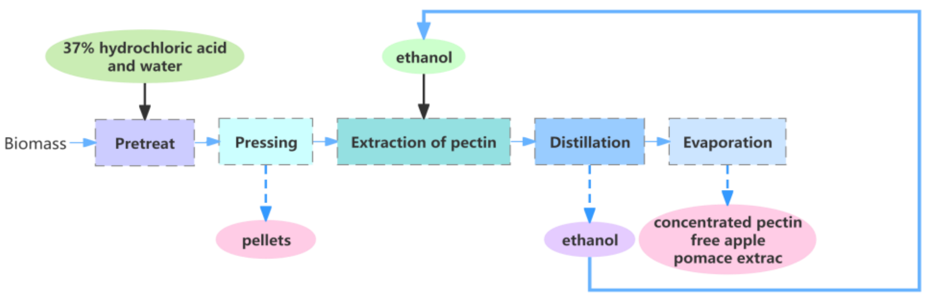

Figure 3: Flowchart of value-added products pectin and others process

3. Case study: Design of a biorefinery for waste valorization

3.1 Process design of biorefinery

We designed a small bio-refinery located in an apple industrial park in Shandong Province. The plant uses the waste residue after apple juice processing as the main feedstocks for sustainable utilization. Given that apple picking is in the summer and autumn season, the plant is set to have only four months of working days per year to match the main harvesting period of the adjacent apple juice plant. Due to its close location, the transportation cost of raw materials can be approximately ignored, and a certain amount of feedstocks collection and procurement costs are charged. The same data is used for the apple pomace feed composition for each process (Table 1). The simulated feed flow is 1 kg/s.

Table 1: Parameters and results (Guerrero et al., 2014)

Parameter	Unit	data
Elemental Analysis		
C	%	47.98
H	%	6.65
N	%	0.78
O	%	37.44
Compositional Analysis		
Cellulose	%	47.49
Hemicellulose	%	27.77
Lignin	%	24.72
Proximate Analysis		
Moisture	%	8.87
Fixed Carbon	%	6.41
Volatile matter	%	81.32
Ash	%	3.40

Although precise biogas production rates are almost impossible to predict because AD involves complex biochemical and biological processes. The AD temperature can be divided into low, medium and high temperature. AD of apple pomace feedstock is simulated under medium temperature condition. The process simulation is based on the anaerobic digestion process simulation model developed by Tamilselvan (2024) with Aspen Plus. The simulation results of this model show that when the organic load rate is 20 g/L, the methane yield can reach up to 520 mL/g VS. Apple pomace was input as virtual component biomass1 in the model. It can be used not only as a simulation of other single-component AD, but also as a simulation of mixed AD of multiple components together, as long as there is sufficient component data.

The simulation process of high pressure washing biogas is proposed (Abu Seman and Harun, 2019) (Figure 4). The thermodynamic properties used are non-random two-liquid (NRTL) methods. Biogas is pressurized in the compressor (COMP1, COMP2) and enters the bottom of the absorption tower, and pressurized water is fed from the top of the absorption tower. The PRODUCT gas contains a large amount of biomethane, which is discharged through the top of the absorber, and the carbon dioxide enriched by the water leaves the absorber and is sent to the flash tower. The gas released from the flash tower is mixed with the raw biogas in the mixer and recycled through the inlet of the COMP2 compressor. The liquid solution leaving the flash tower is transferred to the rectification tower (RadFrac). The purity of bioCH_4 in the PRODUCT stream is suitable for gas grid and vehicle fuel which require more than 95 mole % bioCH_4 purity.

Biomass pyrolysis was modelled as two separate processes: a decomposition block, and a pyrolysis process which produced the pyrolysis products. Both processes were modelled using a YIELD reactor. A FORTRAN calculator determined the C, O_2, N_2, H_2, and H_2O decomposition yields based on the proximate and ultimate analyses of the feed stream. Biogas combustion produces heat and exhaust gases. The heat is used to provide the pyrolysis process and the exhaust gas is sent to the dryer to dry the biomass (Zhang et al., 2017). Vukušić et al. (2021) validated the proposed process for pectin and other value-added product. Three kinds of pectin, granules and pectin free apple pomace extracts were produced. The dry solid particle durability index is 96.9% and the measured net calorific value is 20.312 MJ/kg, which is very similar to the value obtained for wood pellets, so it can be used as a fuel, also as a feed (about $300 /t) or for anaerobic digestion. The pectin free apple pomace extract can be used as an alternative substrate for the production of bread yeast, replacing part of molasses, and has high economic value. Before extraction, the pH value of demineralized water was adjusted with 37% hydrochloric acid to 1. The 93.8% (w / w) ethanol was added in the process to pressure the mixture to obtain solid particles.

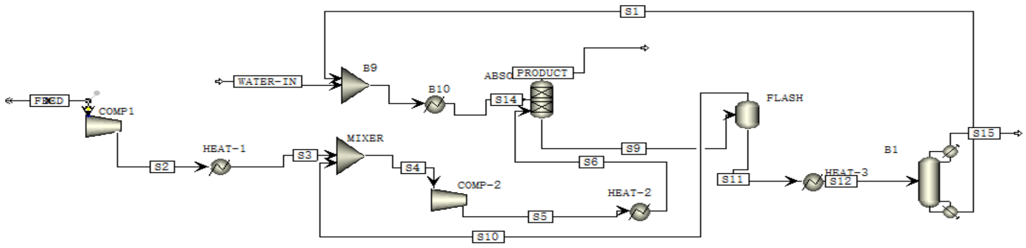

Figure 4: Flowchart of biogas upgrading simulation in Aspen Plus

3.2 Sustainability analysis

Assumed that the discount rate is 10 %. The prices of the products are shown in Table 2. The NPV for each process pathway is calculated in ten years. In scenario 1, the total investment cost is 0.83 M$, the cash flow is -1.19 M$ in 10 years. The NPV of the tenth year was -0.035 M$. The reason for this situation may be due to the low gas production rate of AD for single raw material, which produces a single value-added product. In scenario 2, the total investment cost is 1.08 M$, the cash flow is 5.50 M$. The NPV of the first year was 4.58 M$. Compared with scenario 1, Scenario 2 produces a variety of value-added products and a higher utilization rate of biomass. In scenario 3, the total investment cost is 0.57 M$, the cash flow is 11.93 M$. The NPV of the first year was 0.68 M$ in scenario 3. Also, as a revenue-generating scenario, NPV in Scenario 2 is higher than that in scenario 3. Although Scenario 3 has a lower cost due to the simple process, the price of value-added products produced in Scenario 3 is lower than that of Scenario 2. Above all, Scenarios 2 and 3 are both feasible projects.

Apple pomace AD compost produced 21.3 Nm^3 / t CO_2 during its life cycle (Ampese et al. 2023). As the feed volume of 1,062.72 t/y, carbon emission of this stage is 226,359.36 m^3/y. The coal-to-natural gas process is taken as the carbon emission baseline, and the carbon emissions factors at each stage refer to Liu (2024). CO_2 emissions reached to 628.36 t. After comparison, the emission reduction of Scenario 1 is 59.58 kt. Burning biomass completely is considered to have no net CO_2 emissions. Only the product may cause a CO_2 emission of 142.1 $kgCO_2$-e/t. Therefore, the emission reduction of Scenario 3 process can reach -1.447 Mt.

Table 2: Product prices

Product	Price	Reference
bio-natural gas	$32 / MWh	(Goodell et al., 2024)
bio-char	$200 / t	(Zhang et al., 2017)
bio-oil	$320 / t	
pectin	$10 / kg	(Vaez et al., 2023)
feed	$300/ t	(Vukušić, et al., 2021)
molasses	$100/ t	

4. Conclusions

This paper presents a methodology for biorefinery process design with apple pomace as feedstocks. Three process pathways were designed, simulated, and verified. The results show that the production of pectin and other value-added products (Scenario 3) performs best in the comprehensive environmental and economic analysis. The total investment cost is 0.57 M$, and its emission reduction can reach -1.447 Mt. Although performing well in the economic dimension, pyrolysis process will produce a large amount of carbon emissions. The biogas production still has a lot of room for improvement. The future work can consider the co-fermentation of feedstocks, process improvement, and other value-added products production.

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