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Techno-economic analysis of a grape pomace biorefinery: Production of seed oil, polyphenols, and biochar

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ABSTRACT

Processing grape pomace (GP), a major waste from the wine industry, into multiple value-added products based on the biorefinery concept has a potential to reduce waste disposal and promote a sustainable bioeconomy. However, its economic feasibility at a commercial scale remains unknown. The present study aims to evaluate the economics of a biorefinery process of GP, by performing comparative techno-economic analysis of three processing scenarios: (1) a whole biorefinery process that fully utilizes GP biomass and produces grape seed oil, polyphenols, and biochar (GSO + GSKP + GB), (2) a process that produces grape seed oil and polyphenols (GSO + GSKP), and (3) a process that produces only grape seed oil (GSO). A plant capacity of about 33,000 metric tons/year was considered in the analysis. Among the three scenarios, the whole biorefinery process (GSO + GSKP + GB) showed the highest economic performance with the net present value (NPV), internal rate of return (IRR), and payback period of 111.7 million US-$, 34.3%, and 2.5 years, respectively, due to the diverse revenues and minimized waste disposal cost. The GSO plant showed the lowest economic performance with a negative NPV. Sensitivity analysis revealed that plant capacity, polyphenol price, polyphenol concentration (percentage) in grape pomace, and biochar price had dominating influences on the economic performance of the biorefinery process.

1. Introduction

Grapes are one of the most important fruits in the world, and most grapes are crushed and fermented to make wine. In order to produce 750 L of wine, approximately 1000 kg of grapes are required, generating 120 kg of grape pomace (grape skins, seeds, and some stems), which accounts for about 60% of the total winery solid waste (Jin et al., 2018a; Oliveira and Duarte, 2016). This large amount of grape pomace calls for cost-effective and environmentally sustainable management strategies. Some wineries pay waste management companies to directly dispose grape pomace. Composting grape pomace is an alternative to disposal. It can enrich soil fertility and nutrient recycling, and in the meantime, reduce the cost of waste

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disposal (Bertran et al., 2004). Some countries may have specific requirements for grape pomace treatment. For example, in most European countries, grape pomace and wine lees are sent to distilleries for ethanol and tartaric acid recovery, and an alcoholic beverage called Grappa is made from the distillation of grape pomace (Oliveira and Duarte, 2016). Other current industrialized practices of grape pomace utilization include producing animal feed, generating grape seed/skin powders as additives, extracting grape seed oil for culinary, cosmetic, and pharmaceutical purposes, and extracting grape seed/skin polyphenols as food ingredients, antioxidants, and color (Jin et al., 2019).

The biorefinery concept that integrates processes and technologies to produce multiple value-added products from biomass has received increasing attention due to its clear advantages including: 1) synergistic effects among processes for the reduced energy consumption and labor demands; 2) minimal waste generation because the waste discarded by one process could be the input for another process; 3) diverse revenues due to the generation of multiple products (Jin et al., 2018b). The biorefinery concept has been used in the corn wet milling industry, where a combination of processes and technologies is applied to fractionate corn kernels into corn starch, corn oil, gluten meal, germ meal, and gluten feed (Jin et al., 2018b).

Recently, the biorefinery concept has been applied to valorize grape pomace. In a study of Martinez et al., the supercritical CO_2 extraction was applied to extract polyphenols from grape pomace, and then the polyphenol-free grape pomace was subjected to anaerobic acidogenic digestion to produce volatile fatty acids enriched liquid stream, which was used for polyhydroxyalkanoates production. Finally, the solid leftovers from the acidogenic process underwent the anaerobic methanogenic digestion to produce biogas (Martinez et al., 2016). Jin et al. used hexane to extract seed oil from grape pomace, the solid residue was then mixed with aqueous ethanol solution to extract polyphenols, and the extraction residue which was high in fiber could be either used for producing butanol via pretreatment, hydrolysis, and fermentation (Jin et al., 2018a) or for biochar production via pyrolysis (Jin et al., 2020). Although the biorefinery process of grape pomace showed promising technical feasibility, its economic feasibility at a commercial scale remains unknown. Compared with the traditional process, the biorefinery process is more complex. The potentially increased revenues obtained from multiple products and less waste disposal cost together with the high capital and operation costs of the biorefinery process require a techno-economic evaluation.

Techno-economic analysis is a systematic way for evaluating the technical and economic performance of a designed process. In recent years, techno-economic analysis has been conducted on various waste streams for biorefinery processing. Shahzad et al. provided a detailed economic analysis of the production of polyhydroxyalkanoate (PHA) polymers from the waste generated in the animal processing industry, and found that the PHA production cost varied from 1.7 to 2.0 US-$/kg with the co-products biodiesel (1.2US-$/L) and meat and bone meal (427.5 US-$/ton); and the payback time of the designed process varied from 3.25 to 4.5 years (Shahzad et al., 2017). Arora et al. evaluated the profitability of a mango waste biorefinery processing plant, and found that the production of pectin and seed oil showed the best economic performance with a payback period of 2.4 years (Arora et al., 2018). Another study analyzed the profitability of utilizing sugarcane bagasse in several biorefinery scenarios, annexed to an existing sugar mill. The results showed that compared with traditional combustion of sugarcane bagasse (IRR of 10.3%), producing xylitol together with electricity or glutamic acid in conjunction with electricity proved to be more profitable with IRR of 12.3% and 31.2%, respectively (Özüdoğru et al., 2019). Based on the economic evaluation of previously mentioned waste streams, promising results could be obtained for the generation of multiple products, however, as to the realm of grape pomace biorefinery, techno-economic analysis has seldom been conducted yet.

The present study aims to evaluate the economics of a biorefinery process of GP by performing a comparative techno-economic analysis of three processing scenarios: (1) a whole biorefinery process that fully utilizes GP biomass and produces grape seed oil, polyphenols, and biochar (GSO + GSKP + GB), (2) a process that produces grape seed oil and polyphenols (GSO + GSKP), and (3) a process that produces only grape seed oil (GSO). Each processing scenario was modeled in detail using SuperPro Designer and the economic performance was evaluated based on the internal rate of return (IRR), net present value (NPV), and payback period. Sensitivity analyses were performed to determine the most influential variables affecting the economic performance of the process. Results from this study will provide information to the wine industry to help direct their waste pomace management.

2. Methodology

2.1. *Process description and simulation*

California makes about 85% of all USA wines and generates a large amount of grape pomace (about 435,449 metric tons/year), which provides sufficient raw materials for the grape pomace processing plant (Alston et al., 2018). Therefore, the plant is assumed to be located in California, USA. Since polyphenols are one of the major products and they are enriched in red grape pomace, only red grape pomace is considered as the feedstock in the designed process. Red grape pomace occupies about 50% of the total grape pomace generated (Alston et al., 2018). The grape pomace collection area will cover most of the wineries in North Coast, parts of Central Coast, parts of Inland Valley, and Sierra Foothills of California which are the major wine production areas. Therefore, it is assumed that 15% of the red grape pomace in California could be collected on the conservative side, which corresponds to a processing capacity of 32,659 metric tons (equivalent to 36,000 tons) grape pomace per year. The plant has an operation period of 330 days (11 months) per year and 24 h per day (Somavat et al., 2018). Since wine making is seasonal in nature, the handling process (grape pomace collection and transportation, drying, seed and skin separation) is assumed to be operated on the seasonal basis of 120 days per year to collect and store enough grape pomace for the whole year (330 days) usage, and the rest of the processes (polyphenol extraction, seed oil extraction, and pyrolysis) are operated during the whole 330 days (Dimou et al., 2016). This could be realized by separating the handling process from the biorefinery and increasing the grape pomace throughput of the handing process by 2.75 times in order to shrink the handling processing time from 11 months to 4 months, while the throughput of the biorefinery remains unchanged for the 11-month operation. The SuperPro Designer could help calculate

Table 1 – Key parameters applied in grape pomace biorefinery process.

Parameter	Value[a]
Moisture content of grape pomace after dry	7.8%
Drying temperature	40 °C
Grape seed to grape skin ratio	16:9
Hexane to grape seed ratio	3:1
Hexane extraction temperature	60 °C
Grape seed oil extraction rate	98.7%
Water addition in degumming	30% (w/w) of the seed oil
Degumming temperature	80 °C
Degumming time	1.5 h
NaOH addition in deacidification	0.2% (w/w) of the seed oil
Deacidification temperature	60 °C
Deacidification time	1.5 h
Water addition in water wash	10% (w/w) of the seed oil
Clay addition in bleaching	3% (w/w) of the seed oil
Bleaching temperature	115 °C
Bleaching time	1.5 h
Deodorization temperature	230 °C
Deodorization time	2 h
40% Ethanol to grape oil-free seed and skin ratio	5:1
40% Ethanol extraction temperature	70 °C
Polyphenol extraction rate	82.8%
Final water fraction after evaporation	35%
Ethanol to feed ratio in purification	1:2
Ethanol recovery from solid after desolventizing	80%
Ethanol concentration after distillation	95%
Moisture content of polyphenols	7%
Moisture of seed oil- and polyphenol-free residue after dry	7%
Pyrolysis temperature	500 °C
Biochar yield	37%

[a] Values applied were based on experimental data, industrial quote, and previous techno-economic studies (Brown et al., 2011; Huang et al., 2016; Humbird et al., 2011; Jin et al., 2019; O'brien, 2008; Xu et al., 2009; Xu et al., 2011).

the equipment size/capacity in each section based on their corresponding throughputs. Equipment cleaning and maintenance were scheduled twice per month when the plant is not operating. A clean-in-place (CIP) system is set up for cleaning all equipment (e.g., extractors, refinery and purification tanks, evaporators, and storage tanks) with a cleaning procedure: pre-wash with water (5 min), followed by 3% NaOH wash (80 °C, 40 min), hot water wash (80 °C, 5 min), 2% phosphoric acid wash (30 min), and finally water wash (5 min). Grape pomace composition used in this study is based on a previous study (Jin et al., 2019) and is shown in the Appendix A. Supplementary data (Table A1). It should be noted that the composition of the raw grape pomace is one of the most important factors influencing the product yield and process economics, and its influence was evaluated in the sensitivity analysis.

The designed biorefinery process generates three major products: grape seed oil, grape pomace polyphenols, and biochar. The process block diagram, flow diagram, and key parameters applied in the process are shown in Figs. 1 and 2, and Table 1, respectively. The biorefinery process has the capacity to fully utilize grape pomace to produce multiple products for maximal revenue. However, the large amount of unit operations involved in the production of multiple products increases the capital and operating costs, which may negatively affect the economic performance. To better understand the economic competitiveness of the biorefinery process, the biorefinery process was compared with another two processes where only grape seed oil or seed oil and polyphenols were produced from grape pomace. Therefore, three processing scenarios were considered in this study: (1) a process that produces only grape seed oil (GSO); (2) a process that produces grape seed oil, grape seed and skin polyphenols (GSO + GSKP); (3) a biorefinery process that produces grape seed oil, grape seed and skin polyphenols, and biochar (GSO + GSKP + GB) (process flow diagrams shown in the Appendix A. Supplementary data, Figs. A1, A2, and A3).

2.1.1. *Grape pomace receiving, handling, and separation*

The first step is collecting grape pomace from different wineries and transporting them to the processing plant (Fig. 2, circled with red color). Details of grape pomace collection and transportation including transportation radius, truck loading capacity, and transportation cost are presented in section 2.2.2. After receiving, grape pomace is transferred by a conveyor to a drum dryer, where grape pomace is dried from 50.7% to 7.8% at 40 °C. Dried grape pomace is then transferred to a drum sieve pre-cleaner to remove impurities such as stone and big stems. After that, the grape pomace is subjected to a 3-layer vibrating screen cleaner to separate large grape skins from small grape seeds. Some small skins mixed in grape seeds are further removed by an air recycling aspirator. After these unit operations, grape pomace are separated to grape seeds (64%) and grape skins (36%), which are ground separately using a hammer mill to a particle size of less than 0.85 mm (Jin et al., 2019).

2.1.2. *Grape seed oil extraction and refinery*

Grape seed oil is extracted from the grape seed powders using hexane as an extraction solvent (Fig. 2, circled with blue color). This extraction process was established based on a previous study, which consisted of extracting seed oil, distilling extracted seed oil to remove hexane from seed oil, and desolventizing of spent seed powders to recover hexane (Huang et al., 2016). The seed oil extraction efficiency is set at 98.7% (Appendix A. Supplementary data, Table A2). The hexane free seed oil referred to crude grape seed oil still requires a purification process. The crude grape seed oil purification includes degumming, deacidification, water wash, vacuum drying, bleaching, and deodorization. For this process, the crude grape seed oil is transferred to a refinery tank, where hot water (80 °C) is mixed with crude grape seed oil for 1.5 h for gum removal; after that, NaOH (0.2% of the seed oil) is mixed with the seed oil and water for 10 min, during which NaOH reacts with free fatty acids to form soaps. The mixture is then set for precipitation for 1.5 h at 60 °C for soap and seed oil separation. The separated seed oil is washed by hot water to remove residual soaps, followed by a disk-stack centrifuge to separate the seed oil and the hot water (Huang et al., 2016). Then, a vacuum dryer is used to reduce residual water in seed oil to less than 0.1% (O'brien, 2008). The seed oil is further pumped to a bleaching tank to remove color pigments, where the seed oil is mixed with clay (3%, w/w) at 115 °C for 1.5 h. The spent clay is removed from the refined seed oil by a vibration filter and a bag-type filter. Finally, the refined grape seed oil is obtained after being vacuum heated at 230 °C for 2 h to remove undesirable odors.

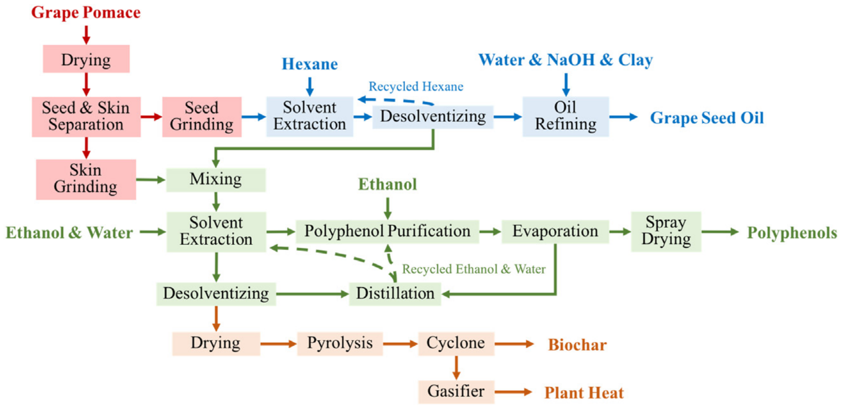

Fig. 1 – The block diagram of the grape pomace biorefinery process to produce seed oil, polyphenols, and biochar.

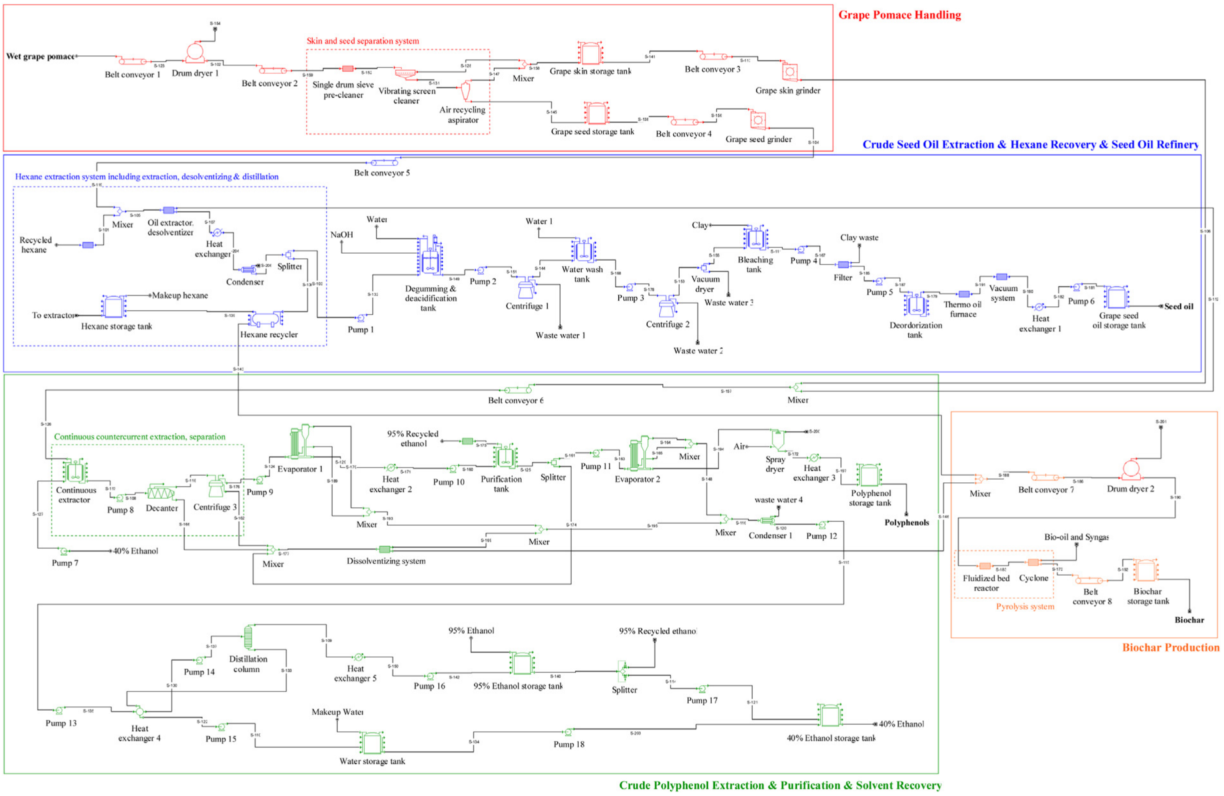

Fig. 2 – The flow diagram of the grape pomace biorefinery process to produce seed oil, polyphenols, and biochar using SuperPro Designer.

2.1.3. *Polyphenol production*

Grape seed residue after seed oil extraction and grape skin powders are combined and used for polyphenol extraction (Fig. 2, circled with green color). The continuous countercurrent extraction is applied to extract polyphenols using ethanol solution (40%, w/w) at 70 °C with a polyphenolic extraction efficiency of 82.8% (Appendix A. Supplementary data, Table A2). A decanter centrifuge is then applied to remove most insoluble residues from solubilized polyphenols, followed by a disk-stack centrifuge to remove trace solid residues. The liquid rich in polyphenols is concentrated to 65% solid content using a two-effect evaporator; the concentrated polyphenol liquid is then purified by adding 95% (w/w) ethanol with a ratio of 1:2 to precipitate about 65% of the impurities. The purified polyphenol liquid is then transferred to an evaporation unit to concentrate polyphenols to about 30% solid content and recycle ethanol. Finally, the concentrated polyphenol liquid is spray dried to obtain polyphenol powder with a moisture content of 7%.

The solid residue after polyphenol extraction is sent to a desolventizer to recover ethanol with an ethanol recovery efficiency of 80% and water recovery efficiency of 20%. The vapor obtained from the desolventizer and the previous two evaporation units are condensed to liquid, which is sent to a distillation system to recover ethanol (Humbird et al., 2011). The ethanol recovered after distillation has a concentration of 95%, and a portion of it is recycled to the ethanol co-precipitation step to remove impurities in crude polyphenolic liquid. The rest of the ethanol and stillage (distillation bottom stream, mainly water) are combined and further adjusted to an ethanol concentration of 40% by adding ethanol/water, which will be recycled and reused in the polyphenol extraction step.

2.1.4. Biochar and plant heat generation

The solid residue obtained after the seed oil and polyphenol production is dried to a moisture content of 7% by a drum dryer and transferred to a fluidized bed reactor by the conveyor (Fig. 2, circled with orange color). In the fluidized bed reactor, the solid residue is converted into biochar, bio-oil, and syngas at 500 °C with a vapor residence time of 5 s in the absence of oxygen under near atmospheric pressure (Brown et al., 2011; Xu et al., 2011). Biochar is recovered by cyclones with a yield of 37%, and the vapor stream containing bio-oil and syngas is combusted to provide heat for the pyrolysis process (e.g., heat to warm up pyrolysis fluid bed unit and carrier gas, and heat required for pyrolysis) and other unit operations for the plant (Xu et al., 2009; Xu et al., 2011). Based on previous studies, the obtained energy after the combustion of co-products (bio-oil and syngas) from 1 kg of grape seed and skin feed could not only support the energy requirement of pyrolysis itself, but also provide 2.7 MJ of extra energy under the conditions mentioned before (Xu et al., 2009; Xu et al., 2011). The extra energy obtained from the combustion of bio-oil and syngas is used as an energy credit to partially replace natural gas needed in the plant based on the lower heating value of natural gas (Xu et al., 2011).

2.2. Economic analysis

2.2.1. Total capital investment

The biorefinery processing model is developed in the SuperPro Designer (version 11.0, Intelligen, Inc., Scotch Plains, NJ), in which various unit operations are used sequentially with the input and output of specific materials and chemicals, and the specific parameters (e.g., time and temperature) set by users. After that, the SuperPro Designer tracks mass flow, determines the mass balance, and calculates energy consumption of the whole process. These data are further used to determine equipment size and quantify. The base cost of each equipment is obtained from references, vendor quotes, or software itself. The changing of process conditions results in automatically adjusted equipment cost depending on the baseline equipment cost input. After determination of equipment cost, direct and indirect costs are calculated to determine the total capital investment, which, together with the operating costs and product revenues, is used to evaluate the economic performance of the designed process (Humbird et al., 2011). The currency used in the model is US-$ and is adjusted to year 2019 based on the Chemical Engineering Plant Cost Index (CEPCI, equation 1) (Humbird et al., 2011). Capital cost is estimated based on the equipment costs, which are derived from budgetary quotations from equipment suppliers (e.g. seed and skin separation set-ups, grinder, continuous countercurrent extraction system, and desolventizing system), previous models (e.g. hexane extraction system, ethanol distillation column, storage tank, condensation, spray drying, centrifuge, belt conveying) (Haas et al., 2006; Huang et al., 2016; Humbird et al., 2011; Kwiatkowski et al., 2006), and SuperPro Designer data base (small and common equipment such as pumps, heat exchanger, and some tanks) (Appendix A. Supplementary data, Table A3). The capacity of equipment varies from different sources, and thus the purchase cost of each equipment used in the current model is adjusted using the exponential scaling expression (equation 2) (Huang et al., 2016).

$$\mathrm{Cost}_{2019} = \mathrm{Cost}_{base} \times (CEPCI_{2019}/CEPCI_{base}) \tag{1}$$

$$\mathrm{Cost}_{new} = \mathrm{Cost}_{base} \times (\mathrm{Size}_{new}/\mathrm{Size}_{base})^{0.6} \tag{2}$$

The purchased equipment together with the cost of equipment installation, instrumentation and controls, processing piping, electrical systems, buildings, yard improvements, and service facilities makes up the total plant direct cost (Peters et al., 2003). The total fixed capital investment consists of total plant direct cost and total plant indirect cost (engineering and supervision, construction expenses, legal expenses, contractor's fee, and contingency) (Humbird et al., 2011). The fixed capital investment together with working capital (10% of the fixed capital investment) and land (1.5% of the fixed capital investment) makes up the total capital investment (Brown et al., 2013; Humbird et al., 2011; Wang et al., 2015). It should be noted that the total capital investment of pyrolysis plant is calculated based on the sizing equation obtained from a previous study, in which various sources of data are used to generate sizing equation to calculate the total capital investment for a biochar plant of up to 120 metric tons dry biomass input per day (Rogers and Brammer, 2012).

2.2.2. Total operating cost

The total operating cost consists of variable operating costs which occurred when the process is operating and fixed operating costs which occurred without regard to whether the plant is operating at full capacity or not (Humbird et al., 2011). The variable operating costs of chemicals (hexane, ethanol, water, clay, NaOH, and phosphoric acid) and utilities (electricity, steam, cooling water, and natural gas) are obtained from various sources including industrial quotes, Independent Commodity Intelligence Services (ICIS) chemical price report, and previous literature (Table 2) (Arora et al., 2018; Campbell et al., 2018; Huang et al., 2016; ICIS, 2019; Statista, 2019; USEIA, 2019). The cost of solid waste disposal was 80 US-$ per metric ton based on the average disposal cost of municipal solid waste in the Pacific states (including California) of USA in 2019 (Statista, 2019). The cost of wastewater discharge was 15 US-$/kgal based on the 2019 average wastewater discharge cost of three cities in California (City of San Carlos, 2019; City of Santa Clara, 2020; San Francisco Water Power Sewer, 2020). The cost of raw grape pomace is assumed to be 32 US-$/metric ton, which is calculated based on the expense of transporting grape pomace from various wineries to the plant. Since the plant is to be built in California, a transportation radius of 200 miles is assumed to cover most of the wineries in North Coast, parts of Central Coast, parts of Inland Valley, and Sierra Foothills. The truck used has a length of 16 m, a height of 2.4 m, and a width of 2.6 m. The loading limit of gross vehicle weight on major highways in the USA is 36.3 metric tons, and considering the tare weight (12 metric tons) of the truck, a net load capacity of 25 metric tons is assumed (Lin et al., 2016). Diesel price (4.11 US-$/gallon) and other operating costs such as driver wages and benefits, truck lease/purchase payments, insurance, licenses, tires, and tolls (1.388 US-$/mile) are also considered to calculate the transportation cost of grape pomace (ATRI, 2019).

It is assumed that GSO, GSO + GSKP, and GSO + GSKP + GB plants have 13, 21, and 29 employees, respectively (Table 2), and with an average annual salary of 50,000 US-$ per person (Huang et al., 2016). Labor burden such as general engineering, payroll overhead (including benefits), safety, plant security, heat, light, and plant communications, is calculated as 90% of the labor salaries (Humbird et al., 2011). The

Table 2 – Variable and fixed operating costs applied in the study.

Item	Value
Variable operating costs[a]	
Wet GP (US-$/metric ton)	32
Hexane (US-$/kg)	0.9
Ethanol (US-$/kg)	0.78
Water (US-$/metric ton)	0.35
Clay (US-$/kg)	0.35
NaOH (US-$/kg)	0.41
Phosphoric acid (US-$/kg)	0.815
Electricity (US-$/kWh)	0.065
Steam (US-$/metric ton)	17
Cooling water (US-$/metric ton)	0.05
Natural gas (US-$/metric ton)	184
Solid waste (US-$/metric ton)	80
Liquid waste (US-$/kgal)	15.15
Fixed operating costs[b]	
Plant personnel	
Plant manager	1
Plant Engineer	1
Lab manager	1
Lab Technician	1
Maintenance technician	2, 4, and 6 for GSO, GSO + GSKP, and GSO + GSKP + GB plants, respectively
Shift operators	6, 12, and 18 for GSO, GSO + GSKP, and GSO + GSKP + GB plants, respectively
Clerks	1
Total	13, 21, and 29 for GSO, GSO + GSKP, and GSO + GSKP + GB plants, respectively
Average labor salaries (US-$/year)	50,000
Labor burden	90% of the labor salaries
Maintenance	3% of inside-battery-limits equipment costs, annually
Property insurance	0.7% of fixed capital investment, annually
General expenses	
Distribution and market cost[c]	10% of total operating cost
Research and development cost[c]	5% of total operating cost

[a] Wet grape pomace cost was charged by transportation. Other variable operating costs are obtained from various sources including industrial quotes, ICIS chemical price report, and previous literature (Arora et al., 2018; Campbell et al., 2018; Huang et al., 2016; ICIS, 2019; Statista, 2019; USEIA, 2019).

[b] The calculation of fixed operating costs was based on previous literature (Humbird et al., 2011).

[c] The calculation of general expenses was based on previous literature (Max et al., 2003).

Table 3 – Total capital investment (million US-$) for GSO, GSO + GSKP, and GSO + GSKP + GB plants.

Item	GSO	GSO + GSKP	GSO + GSKP + GB
Feedstock handling	2.1	2.1	2.1
Seed oil production	2.4	2.4	2.4
Polyphenol production	–	4.6	4.6
Biochar production	–	–	2.6
Storage	0.3	0.7	0.7
CIP system	0.1	0.1	0.1
Total equipment cost (E)	4.8	9.8	12.5
Purchased-equipment installation (39% E)	1.9	3.8	4.9
Instrumentation and controls (26% E)	1.3	2.6	3.2
Piping (31% E)	1.5	3.0	3.9
Electrical systems (10% E)	0.5	1.0	1.2
Buildings (29% E)	1.4	2.9	3.6
Yard improvements (12% E)	0.6	1.2	1.5
Service facilities (55% E)	2.7	5.4	6.9
Total direct costs	14.6	29.7	37.7
Engineering and supervision (32% E)	1.5	3.1	4.0
Construction expenses (34% E)	1.6	3.3	4.2
Legal expenses (4% E)	0.2	0.4	0.5
Contractor’s fee (19% E)	0.9	1.9	2.4
Contingency (37% E)	1.8	3.6	4.6
Total indirect costs	6.1	12.4	15.7
Fixed capital investment (FCI)	20.7	42.1	53.4
Working capital (10% of FCI)	2.1	4.2	5.3
Land (1.5% of FCI)	0.3	0.6	0.8
Total capital investment	23.0	46.9	59.6

Table 4 – Annual usage of raw material, chemicals, and utilities and waste generation of GSO, GSO + GSKP, and GSO + GSKP + GB plants.

Item	GSO	GSO + GSKP	GSO + GSKP + GB
Grape pomace (metric ton)	32,659	32,659	32,659
Chemicals			
Ethanol (kg)	–	2,575,449	2,575,449
Hexane (kg)	67,051	67,051	67,051
Clay (kg)	48,866	48,866	48,866
NaOH (kg)	5441	7,487	7,751
Phosphorous acid (kg)	1452	2,816	2,992
Water (metric ton)	3,630	17,169	17,530
Utilities			
Electricity (kWh)	1,978,389	6,518,652	6,647,120
Steam (metric ton)	6890	109,953	109,963
Cooling water (metric ton)	780,359	13,188,705	13,188,705
Natural gas (metric ton)	1,077	1,110	1,122
Waste to dispose			
Solid waste (metric ton)	15,940	26,509	51
Wastewater (kgal)	959	1,961	2,056

maintenance materials are calculated as 3% of the inside-battery-limits equipment (the equipment in grape seed oil extraction, polyphenol extraction, and biochar production areas) costs (Humbird et al., 2011). Property insurance is estimated as 0.7% of the fixed capital investment (Humbird et al., 2011). The depreciation cost is calculated based on the 10-year straight-line method with the depreciation rate set at 10% of the fixed capital investment per year (Todd and Baroutian, 2017). For the general expenses, distribution and market cost, and research and development cost are assumed to be 10% and 5% of the total production cost, respectively (Max et al., 2003).

2.2.3. *Revenues and profitability analysis*

After calculating the total capital and operating costs, the next step is to evaluate the revenues obtained from selling the products. The selling prices of grape seed oil, polyphenols, and biochar are set to be 4 US-$/kg, 20 US-$/kg, and 2.47 US-$/kg, respectively, based on the average price in the market and literature (Campbell et al., 2018; Dimou et al., 2016; Duba and Fiori, 2019; Todd and Baroutian, 2017). It is worth noting that the market prices of these three products are highly variable and the prices chosen in this study are quite conservative in the market. The plant lifetime is assumed to be 20 years, with two additional years of construction and start up (40% and 60% the total capital investment allocation for the first and second year, respectively) (Huang et al., 2016). The plant is 100% equity financed. Income taxes are calculated as 35% of the taxable income (Somavat et al., 2018). The economic performance of the process is evaluated by NPV, IRR and payback period. NPV is the sum of the present values of future cash flows for a certain period of time (Towler and Sinnott, 2012). NPV is calculated by assuming the plant operating time of 20 years with a discount rate of 10%. IRR is the discount rate at which the NPV is zero after taxes (Humbird et al., 2011). IRR provides the profit of the plant considering the time value of money, and indicates the yield of an investment (Kwan et al., 2015). Payback period is calculated from the total capital investment divided by the average annual cash flow, and provides the time required to recoup the investment (Towler and Sinnott, 2012).

2.2.4. *Sensitivity analysis*

Sensitivity analysis was performed to assess the impact of changes/uncertainties of the investment, operating cost, and market fluctuations on the economic performance (e.g., NPV) of the biorefinery process. Different parameters including plant capacity, variations in grape pomace compositions (e.g., seed oil and polyphenol percentages), grape pomace cost, grape seed oil and polyphenol extraction efficiencies, the selling prices of grape seed oil, polyphenols, and biochar, the costs of steam and electricity, waste disposal, and labor were considered. The effect of operating days on the NPV and IRR of different scenarios was also evaluated.

3. Results and discussion

3.1. *Capital costs of the grape pomace biorefinery plants*

The estimation of the total capital investment (TCI) is summarized in Table 3. The TCI of the GSO, GSO + GSKP, and GSO + GSKP + GB plants was estimated to be 23.0 million US-$, 46.9 million US-$, and 59.6 million US-$, respectively. The major contribution to the TCI was the equipment cost for all three plants. GSO + GSKP + GB plant had the highest purchased equipment cost (12.5 million US-$), followed by GSO + GSKP (9.8 million US-$) and GSO (4.8 million US-$) plants. This was apparent because the GSO + GSKP + GB plant had the highest equipment quantities for the production of multiple products. In the GSO + GSKP + GB plant, polyphenol production section had a total equipment purchase cost of 4.6 million US-$, which was comparable to that in previous studies (antioxidants extraction from wine lees or grape pomace) (Dimou et al., 2016; Duba and Fiori, 2019). In addition, the equipment cost in the polyphenol production section was the major contributor to the total equipment cost, and the ethanol recovery system (desolventizer, distillation, and evaporation) contributed the most in the polyphenol production section.

3.2. *Total operating cost*

The annual usage of raw material, chemicals, utilities, and waste generation is shown in Table 4. As to the chemical demand, water and ethanol showed the highest usages in

Table 5 – Operating cost of GSO, GSO + GSKP, and GSO + GSKP + GB plants.

Operating cost (million US-$/year)	GSO	GSO + GSKP	GSO + GSKP + GB
Grape pomace	1.1 (15.3%)[a]	1.1 (6.3%)	1.1 (6.4%)
Chemicals			
Ethanol	–	2.0 (12.1%)	2.0 (12.3%)
Hexane	0.06 (0.9%)	0.06 (0.4%)	0.06 (0.4%)
Clay	0.02 (0.3%)	0.02 (0.1%)	0.02 (0.1%)
NaOH	0.002 (0.03%)	0.003 (0.02%)	0.003 (0.02%)
Phosphorous acid	0.001 (0.02%)	0.002 (0.01%)	0.002 (0.01%)
Water	0.001 (0.02%)	0.006 (0.04%)	0.006 (0.04%)
Total chemicals	0.1 (1.2%)	2.1 (12.6%)	2.1 (12.9%)
Utilities			
Electricity	0.1 (1.9%)	0.4 (2.6%)	0.4 (2.7%)
Steam	0.1 (1.7%)	1.9 (11.3%)	1.9 (11.5%)
Cooling water	0.04 (0.6%)	0.7 (4.0%)	0.7 (4.0%)
Natural gas	0.2 (2.9%)	0.2 (1.2%)	0.2 (1.3%)
Total utilities	0.5 (7.1%)	3.2 (19.0%)	3.2 (19.4%)
Waste to dispose			
Solid waste disposal	1.3 (18.7%)	2.1 (12.8%)	0.004 (0.03%)
Wastewater discharge	0.01 (0.2%)	0.03 (0.2%)	0.03 (0.2%)
Total waste to dispose	1.3 (18.9%)	2.2 (13.0%)	0.04 (0.2%)
Labor	1.2 (18.0%)	2.0 (12.0%)	2.8 (16.9%)
Equipment maintenance	0.1 (1.6%)	0.4 (2.1%)	0.5 (3.0%)
Property insurance	0.1 (1.5%)	0.2 (1.3%)	0.3 (1.7%)
Depreciation	1.5 (21.4%)	3.1 (18.6%)	4.0 (24.4%)
Distribution and market cost	0.7 (10.0%)	1.7 (10.0%)	1.6 (10.0%)
Research and development cost	0.3 (5.0%)	0.8 (5.0%)	0.8 (5.0%)
Total operating cost	6.9	16.6	16.3

[a] Number in parenthesis represents the operating cost share (%) of each category.

the GSO + GSKP and GSO + GSKP + GB plants because these two plants used a large amount of aqueous ethanol solution to extract and purify polyphenols. Besides ethanol and water, the plants also consumed different amounts of other chemicals, including hexane, clay, and sodium hydroxide for the production of grape seed oil and biochars. In terms of utilities (electricity, steam, cooling water, and natural gas), the GSO + GSKP + GB plant had the highest utility consumption because it had the most unit operations, followed by the GSO + GSKP and GSO plants. As to the waste generation, the GSO + GSKP + GB plant had the least amount of solid waste because the solid waste generated after grape seed oil and polyphenol extraction was pyrolyzed to biochar. Only 51 metric tons of solid waste was generated per year in the GSO + GSKP + GB plant, which was 0.2% of the original grape pomace input (32,659 metric tons per year). This was promising as more than 99% of the grape pomace waste was reduced. On the other hand, the GSO and GSKP plants generated 15,940 and 26,509 metric tons of solid wastes, respectively, representing 48.8% and 81.2% of the original grape pomace input. The higher weight of solid waste generated in the GSO + GSKP plant compared with that in the GSO plant was due to the moisture difference of the wastes generated in the two plants. In GSO + GSKP plant, the solid residue was wet after polyphenol extraction using aqueous ethanol and water solution, while in the GSO plant, the solid residue was dry after hexane extraction and desolventizing. Most of the wastewater was generated from the CIP cleaning of equipment, and the GSO + GSKP + GB plant produced the highest amount of wastewater to discharge because it had the most equipment to clean.

The total annual operating costs of 6.9 million US-$, 16.6 million US-$, and 16.3 million US-$ were calculated for the GSO, GSO + GSKP, and GSO + GSKP + GB plants, respectively (Table 5). Although the GSO + GSKP + GB plant had more unit operations, chemical and utility usages than the GSO + GSKP plant has, it showed a lower annual operating cost, which was mainly due to the minimized disposal cost in the GSO + GSKP + GB plant (Table 5). In addition, if the grape pomace was disposed as it was, the annual cost for disposing 32,659 metric tons of grape pomace would be 2,628,000 US-$, which was remarkably higher than the annual solid waste disposal cost of GSO + GSKP + GB plant (Table 5).

Table 5 also shows the contribution of each category to the total operating cost. For GSO and GSO + GSKP + GB plants, the depreciation cost had the highest contribution to the total operating cost. Besides the depreciation cost, for the GSO plant, the waste disposal component had the second highest contribution to the total operating cost which was due to the generation of a large amount unexploited grape skins and oil free grape seeds. For the GSO + GSKP + GB plant, the utility component was the second major contributor to the total operating cost, and for the GSO + GSKP plant, the utility component was the highest contributor to the total operating cost, followed by depreciation cost. The high utility costs in the GSO + GSKP and GSO + GSKP + GB plants were due to a series of unit operations in the polyphenol production section, in which high amounts of electricity, steam, and cooling water were used to extract/purify polyphenols and recycle ethanol (Table 4).

3.3. *Revenue and profitability analysis*

Product yield is one of the important factors that affect the revenue and profitability of the plant. From Table 6, we could see that from 1 metric ton of wet GP, 49.7 kg grape seed oil, 40.6 kg polyphenols, and 161.7 kg biochar could be produced after the biorefinery process (GSO + GSKP + GB plant). Biochar

Table 6 – Product yield, annual production, and revenue obtained from grape pomace biorefinery processes.

Item	Yield (kg/metric ton wet grape pomace)	Quantity (metric ton/year)	Revenue (million US-$/year)		
			GSO	GSO + GSKP	GSO + GSKP + GB
Grape seed oil	49.7	1,627	6.5 (100)[a]	6.5 (19.7)	6.5 (14.1)
Polyphenols	40.6	1,329	–	26.6 (80.3)	26.6 (57.6)
Biochar	161.7	5,293	–	–	13.1 (28.3)
Total revenue	–	–	6.5	33.1	47.7

[a] Number in parenthesis represents the operating cost share (%) of each category.

Table 7 – Economic indicators (NPV, IRR, and payback period), the minimum selling prices of products, and the minimum plant capacity of GSO, GSO + GSKP, and GSO + GSKP + GB plants.

Item	GSO	GSO + GSKP	GSO + GSKP + GB
NPV (million US-$)	−11.8	55.4	111.7
IRR (%)	−1.6	26.3	34.3
Payback period (year)	17.0	3.3	2.5
Minimum selling price of seed oil (US-$/kg)	5.6	ND[a]	ND
Minimum selling price of polyphenols (US-$/kg)	–	10.9	1.6
Minimum selling price of biochar (US-$/kg)	–	–	ND
Minimum plant capacity (metric ton/year)	57,153	3,797	1,814

[a] Minimum selling price of the product is not determined since NPV stays positive even though the product has no price.

showed the highest yield due to the high fiber content in grape pomace being converted to biochar during pyrolysis (Jin et al., 2019), followed by grape seed oil and polyphenols. As to the annual production, the same trend was found – biochar shows the highest annual production (5293 metric tons/year), followed by grape seed oil (1627 metric tons/year) and polyphenols (1329 metric tons/year). Considering the selling prices of polyphenols (20 US-$/kg), grape seed oil (4 US-$/kg), and biochar (2.47 US-$/kg), the total annual revenues obtained in the GSO, GSO + GSKP, and GSO + GSKP + GB plants were 6.5 million US-$, 33.1 million US-$, and 47.7 million US-$, respectively (Table 6). Compared with the GSO plant, the GSO + GSKP and GSO + GSKP + GB plants had higher revenues, which were mainly attributed to the high revenue from the selling of polyphenols (occupying 80.3% and 57.6% of the total revenue in the GSO + GSKP and GSO + GSKP + GB plants, respectively).

The revenue from grape seed oil was lower than that from polyphenol and biochar (Table 6). This was due to the small production volume of grape seed oil from each metric ton of grape pomace as well as its lower selling price compared with polyphenols. The selling price of grape seed oil was chosen at 4 US-$/kg in this study. A previous study stated the minimum selling price of extra virgin grape seed oil was 14 US-$/kg, and the average price of the grape seed oil could vary from 2 to 42 US-$/kg based on the retail selling price (Duba and Fiori, 2019). Since the seed oil obtained from current study was extracted by hexane, its selling price was expected to be lower than the premium expeller-pressed grape seed oil; therefore, the 4 US-$/kg was a relatively conservative and reasonable selling price. It should be mentioned that the selling price of the products and product yield have large variations and potentially affect the revenue and economic performance of the designed process. Thus, the variations were further explored and evaluated in the following sensitivity analyses.

Based on the results of total capital costs, total operating costs, and revenues, the economic performances of the three plants were evaluated using NPV, IRR, and payback period as the indicators. Although the GSO + GSKP + GB plant had the highest total capital cost, it provided multiple products for generating a high revenue. From Table 7 we could see that the IRR for the GSO + GSKP + GB plant was 34.3%, with a NPV of 111.7 million US-$ and a payback period of 2.5 years. Although the biorefinery process of GP is new to the industry at the current stage, the products (grape seed oil, grape polyphenols and biochars) from the process already has an established market. Therefore, the level of risk of the designed biorefinery process could be considered as medium (Peters et al., 2003). The positive NPV, the 34.3% of IRR, and the payback period of 2.5 years obtained from the techno-economic analysis suggested an economically feasible investment for this medium-risk biorefinery process. Compared with GSO + GSKP + GB plant, the GSO + GSKP plant had lower revenue with the NPV, IRR, and payback period of 55.4 million US-$, 26.3%, and 3.3 years, respectively. The GSO plant produced grape seed oil as the sole product and had the worst economic performance among the three plants, showing a negative NPV of −11.8 million US-$, the lowest IRR of −1.6%, and the longest payback period of 17.0 years, which was considered as economically unfavorable.

3.4. *Sensitivity analysis*

The mostly likely values for processing parameters used in the processes are discussed so far. Due to the uncertainty of several input parameters, single-point sensitivity was conducted to identify the most influencing parameters on the economic performance of the processes. Both low- and high-side values of the uncertain parameters were selected based on the actual ranges of a specific parameter or a certain percentage variation of the base case.

3.4.1. *GSO + GSKP + GB plant*

As to the GSO + GSKP + GB plant, plant capacity was the dominant parameter influencing the economic performance of the process (Fig. 3a). Increasing the plant capacity from processing 15% (32,659 metric tons/year) to 30% (65,318 metric tons/year) of California red grape pomace resulted in a 139.1% increase on NPV. On the other hand, scaling down the plant capacity from 15% to 7.5% (10,886 metric tons/year) of California red grape pomace resulted in a NPV decrement from 111.7 million US-$ to 39.5 million US-$.

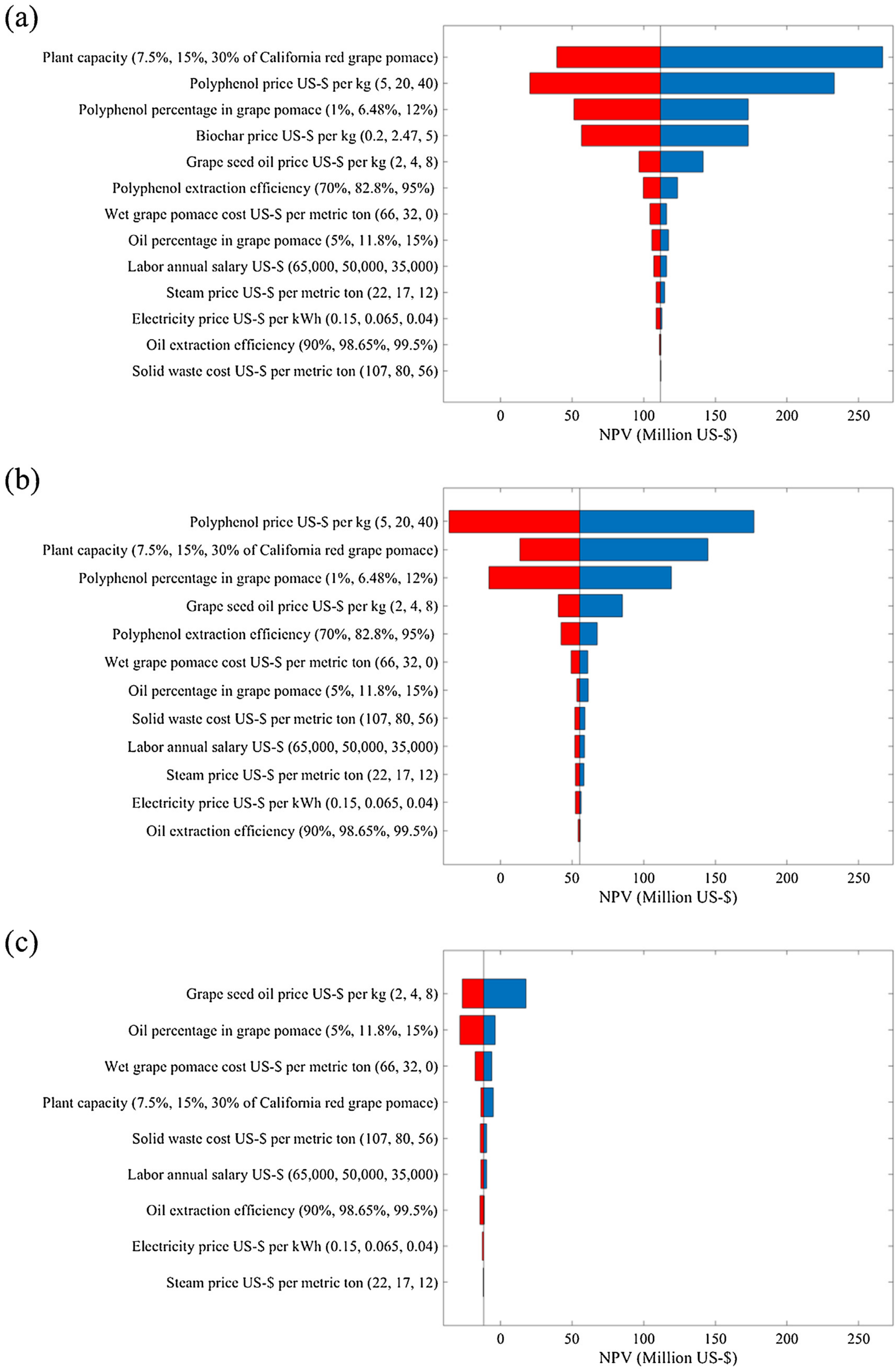

Fig. 3 – Sensitivity of NPV (million US-$) of different parameters for (a) GSO + GSKP + GB, (b) GSO + GSKP, and (c) GSO.

The second major parameter that influences the economic performance was the polyphenol price. Polyphenol is a high-value commodity and the selling prices of polyphenol vary a lot in different references. A study used 64 US-$/kg as the base value for grape pomace polyphenols in economic analysis and applied a price range of 32 to 193 US-$/kg in the sensitivity analysis (Todd and Baroutian, 2017). Another study systematically evaluated the minimum selling price of the antioxidant-rich extract of winery waste and calculated the polyphenolic extract selling price with a range from 11.06 to 122 US-$/kg under different conditions (Dimou et al., 2016). The current grape pomace polyphenol selling price on the market can be found from 5 to 100 US-$/kg or even higher depending on the purity of polyphenols, quantity of purchase, and specific active compounds existing in extract powders. In this study, the polyphenol selling price was assigned to a market value of 20 US-$/kg in the base case, which was modest in current market. In the sensitivity analysis, the lowest and highest bounds of polyphenol price were assigned to be 5 US-$/kg and 40 US-$/kg, respectively. From the result (Fig. 3a), it could be seen that NPV increased from 20.5 to 233.2 million US-$ as the polyphenol price increased from 5 to 40 US-$/kg.

The variation of biochar price also showed a high impact on the NPV of the GSO + GSKP + GB plant. The selling price of biochar was set at 2.47 US-$/kg in the base case, which was determined based on the survey of 23 biochar sellers in the USA (Campbell et al., 2018). However, the biochar price is highly dependent on the chemical and physical properties of biochar, diversity of potential usages (e.g., adsorbent and soil conditioners), and the associated markets (e.g., agriculture, mining, horticulture, forestry, and industrial adsorbent sectors) (Brown et al., 2011; Campbell et al., 2018). Several organizations such as International Biochar Initiative (IBI) and European Biochar Certificate (EBC) are still working on establishing relevant biochar standards (Campbell et al., 2018). Therefore, we set a relatively large range of biochar price from 0.2 to 5 US-$/kg (based on other studies and market price) (Brown et al., 2011; Campbell et al., 2018), which caused the NPV increased from 56.7 to 172.9 million US-$, respectively. The variation of selling price for grape seed oil (from 2 to 8 US-$/kg) did not show a remarkable impact compared with that for polyphenols and biochar.

The effect of composition, especially polyphenol content/percentage, in GP was also important to the economic performance of the GSO + GSKP + GB plant (Fig. 3a). The polyphenol content range was set from 1% to 12% of dry red GP which was based on previous studies (Chamorro et al., 2012; Jin et al., 2019). When the polyphenol content was set at 1% of dry GP (low side), the NPV was only 51.5 million US-$, which was 53.9% lower than that of the base case (6.5% of polyphenols in dry GP). When the polyphenol content increased to 12% of dry GP, the NPV increased to 173.1 million US-$, which was 55.0% higher than that of the base case. The grape seed oil content showed a smaller impact on economics but with a similar trend — NPV increased from 105.7 million US-$ to 117.3 million US-$ when increasing grape seed oil content from 5% to 15% of dry GP. The variations in product (polyphenol and seed oil) extraction efficiencies showed a small impact. It was worthy of noting that shifting the raw GP collecting cost from 66 US-$/metric ton to 0 US-$/metric ton did not show a high impact on NPV. In addition, the variations in utility (steam and electricity) price, labor cost, and solid waste disposal cost had minimal effects on the economic performance. Therefore, it might be worthy to invest more on polyphenol production and purification processes to produce polyphenols with a high purity (selling price) and run the GSO + GSKP + GB plant with a large processing capacity.

3.4.2. GSO + GSKP plant

For the GSO + GSKP plant, polyphenol price, plant capacity, and polyphenol percentage/content in dry grape pomace were the three major factors influencing the plant economic performance (Fig. 3b). Increasing the polyphenol price from 20 US-$/kg (base case) to 40 US-$/kg resulted in an increase of NPV from 55.4 million US-$ to 176.9 million US-$, while reducing the price to 5 US-$/kg resulted in a negative NPV of −35.8 million US-$. Similar to the GSO + GSKP + GB plant, plant capacity also played an important role in determining the economic performance. It was found that increasing the plant capacity from 15% to 30% of California red grape pomace input increased the NPV from 55.4 million US-$ to 144.7 million US-$, while scaling down the plant capacity to 7.5% resulted in a decrease of NPV to 13.7 million US-$ (Fig. 3b). The variation of polyphenol content (from 1% to 12%) in dry grape pomace also played a big role in determining the NPV (from −8.0 to 119.4 million US-$, respectively). On the other hand, the variations of labor cost, steam and electricity prices, and grape seed oil extraction efficiency showed minimal impacts on the economic performance of the GSO + GSKP plant.

3.4.3. GSO plant

For the GSO plant, since grape seed oil is the only product, variations in grape seed oil price and oil content in GP played crucial roles in the overall economics (Fig. 3c). When the grape seed oil price increased by two-fold from 4 to 8 US-$/kg, the NPV increased from a negative value (−11.8 million US-$) to a positive value (18.0 million US-$), making this venture economically favorable. A reverse trend was found when decreasing the grape seed oil price from 4 US-$/kg to 2 US-$/kg, leading to a reduced NPV of −26.6 million US-$. An increase of seed oil content from 11.8% to 15% in GP increased the NPV, but was still economically unfeasible. The impacts of raw material price, plant capacity, and waste disposal cost to the NPV of the GSO plant were moderate, and the impact of electricity and steam price played minimal influence on the economic feasibility of the GSO plant.

3.4.4. Minimum product selling price and plant capacity

Since the variations in product selling price and plant capacity played big roles in economic performance of the three plants based on the single-point sensitivity analysis (Fig. 3), the minimum selling price of the products and the minimum plant capacity were calculated by NPV equaling to zero. In the GSO plant, grape seed oil was the only product and its minimum selling price was 5.6 US-$/kg (Table 7), which was reasonable compared with the market seed oil price of 2 to 42 US-$/kg, but was lower than the minimum selling price of extra virgin grape seed oil (14 US-$/kg) reported in a previous study (Duba and Fiori, 2019). As to the GSO + GSKP and GSO + GSKP + GB plants, the production of biochar from grape seed and skin extract residues significantly reduced the minimum selling price of polyphenols from 10.9 US-$/kg (GSO + GSKP) to 1.6 US-$/kg (GSO + GSKP + GB), indicating that the GSO + GSKP + GB plant had more power to resist the financial risk of fluctuating market price of polyphenols (Table 7). In addition, the minimum selling prices of seed oil and/or biochar were not found in GSO + GSKP or GSO + GSKP + GB plant since the NPV remained positive even though they had 'zero' selling prices in the market. The minimum plant capacity was also determined. The GSO, GSO + GSKP, and GSO + GSKP + GB plants showed a minimum plant capacity of 57,153, 3797, and 1814 metric tons/year, respectively. Given that California generates about 435,449 metric tons/year of grape pomace, collection of sufficient amounts of grape pomace should not be a problem, but it should be noted that there is potential uncertainty regarding the equipment sizes, costs, and logistics in the calculation of minimum plant capacity.

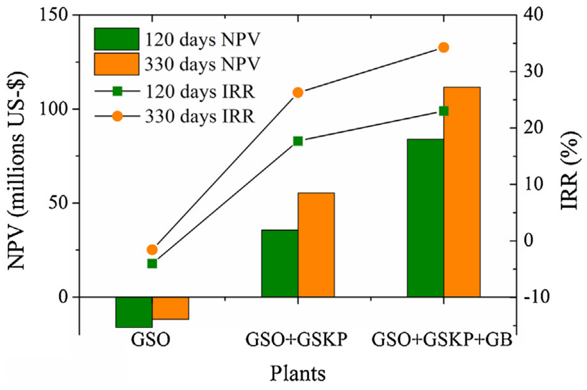

Fig. 4 – The effect of operating days on the NPV and IRR of GSO, GSO + GSKP, GSO + GSKP + GB plants.

3.4.5. *Operating days of the grape pomace biorefinery plants*

The operating days have a significant influence on the economic performance of the grape pomace biorefinery plants. Because grape pomace is a seasonal byproduct generated from winemaking and is highly perishable, the process is designed to collect and dry grape pomace during the four-month winemaking season and the rest processes are operated for the whole year (330 days), with the purpose of extending plant operation period, reducing equipment sizes (costs), and maximizing process economics. However, it has been reported that a long-term storage (over 4 months) of the biomass might lead to the loss of polyphenols (Arora et al., 2018). In addition, the quality of oil in grape seeds might also change over time. Therefore, one consideration was to operate the whole plant within four months (120 days) to avoid any degradation of valuable components in grape pomace during long time storage. As a result, reducing the operating days to 120 days reduced the IRR and NPV for all plants (Fig. 4). For the GSO + GSKP + GB plant, the NPV reduced from 111.7 million US-$ (330 days) to 84.1 million US-$ (120 days), which had brought down IRR from 34.3 to 23.0% and increased the payback time from 2.5 to 3.8 years. Therefore, the balance between a short operating time to avoid the degradation of valuable compounds and a long operating time to gain more profit needs further consideration.

Compared to the other two plants (GSO + GSKP and GSO + GSKP + GB), the plant only producing grape seed oil (GSO) was economically unfavorable with a negative NPV. This was probably because of the low selling price of the grape seed oil extracted by hexane. In the grape seed oil industry, there is an increasing trend to produce high-quality grape seed oil (and thus a high selling price) using expeller presses or include two production lines (expeller-pressed and hexane extracted grape seed oil) to increase the overall profit. In the future, it would be meaningful to investigate the effect of different oil extraction methods (e.g., expeller-pressing and hexane extraction) on the overall economic performance of the integrated process. Moreover, it would be also interesting to investigate other process scenarios, such as only considering the polyphenol and biochar production from grape pomace, when experimental results are available. Nevertheless, the results obtained from this study provide basic information regarding the grape pomace biorefinery and set an example for upcycling of other agro-industrial wastes.

4. Conclusions

The techno-economic model of grape pomace biorefinery process was developed with three scenarios: a single-product scenario (grape seed oil, GSO), a dual-product scenario (grape seed oil and polyphenols, GSO + GSKP), and a whole biorefinery scenario (grape seed oil, polyphenols, and biochar, GSO + GSKP + GB). Among the three scenarios, the GSO + GSKP + GB scenario showed the best economic performance with the NPV, IRR, and payback period of 111.7 million US-$, 34.3%, and 2.5 years, respectively, which was considered economically viable. Sensitivity analysis showed that plant capacity, polyphenol price and content, and biochar price had a major impact on the economic performance of the GSO + GSKP + GB plant. Overall, this study demonstrated that biorefinery of GP to produce multiple products is technically and economically feasible at a commercial scale.

Declaration of interests

None.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.fbp.2021.02.002.

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