Trabajo Fin de Grado

Simulation Study of Process Flow Design for Downstream Processing of Succinic Acid Production Using SuperPro Designer® Software

Autor/es

Rini Hazwani Binti Rithuan

Director/es

Dr Law Jeng Yih
José Luis Sánchez Cebrián

Escuela de Ingeniería y Arquitectura

2021

SIMULATION STUDY OF PROCESS FLOW DESIGN FOR DOWNSTREAM PROCESSING OF SUCCINIC ACID PRODUCTION USING SUPERPRO DESIGNER SOFTWARE

RINI HAZWANI BINTI RITHUAN

Malaysian Institute of Chemical & Bioengineering Technology
Universiti Kuala Lumpur

JULY 2021

SIMULATION STUDY OF PROCESS FLOW DESIGN FOR DOWNSTREAM PROCESSING OF SUCCINIC ACID PRODUCTION USING SUPERPRO DESIGNER SOFTWARE

RINI HAZWANI BINTI RITHUAN
55200221001

Report Submitted to Fulfill the Partial Requirements
For the Bachelor of Chemical Engineering (Hons.)

Malaysian Institute of Chemical & Bioengineering Technology
Universiti Kuala Lumpur

JULY 2021

DECLARATION

I declare that this report is my original work and all references have been cited adequately as required by the University.

Signature : [redacted]

Name : [redacted]ZWANI BINTI RITHUAN

ID No. : 55200221001

Date :

APPROVAL PAGE

We have supervised and examined this report and verify it meets the program and University's requirements for the Bachelor in Chemical Engineering (Hons.)

Signature :

Supervisor : Dr. Law Jeng Yih

Official Stamp :

Date :

ACKNOWLEDGEMENT

In the name of God, Most Gracious, Most Merciful.

First and foremost, I would like to express my gratitude to my supervisor, Dr Law Jeng Yih for his guide and support throughout this project. Also million thanks to my lecturer, who is such a great mentor and a role model to me, Lola Mariscal Masot for her sincere and full support to me throughout my degree years in a foreign land. I would not be here without her help, *muchicimas gracias* Lola. I also would like to thank my parents and family for the endless support and love.

Last but not least, thank you to everyone who was involved directly and indirectly in the completion of this thesis. Thank you.

ABSTRACT

Succinic acid has various uses in multiple industries such as food, pharmaceutical and chemical industries. Succinic acid was traditionally produced petro-chemically. Due to various factors such as alarming environmental impacts and expensive catalysts costs, the biological method of succinic acid production from fermentation broth has been applied widely. However, the downstream recovery process is known to be a costly one. SuperPro Designer® is a software that can be applied to conduct economic analysis of this downstream recovery process. For that reason, the purpose of this research to utilize SuperPro Designer® software in creating a complete flowsheet of the downstream recovery process using initial data and operating conditions from previous experimental works. Using the flowsheet that had been created, the final composition of succinic acid was obtained. Then, economical evaluation was carried out for the downstream process. Results obtained demonstrated that 3545.07 kg/batch of 98% pure succinic acid crystals were obtained as the final product. Economic evaluation showed noteworthy results as the process is deemed viable and economically feasible according to the Economy Evaluation Report (EER). The payback time was 2.88 years and the unit production cost was estimated to be 23.40 MYR/kg. Sensitivity analysis was also carried out and results showed that the process is still viable at ±25% cost of fermentation process while it showed a negative Net Present Value (NPV) at a 25% decrement in the selling price of succinic acid. Results found in this research demonstrated the potential of using SuperPro Designer® as a simulation tool in estimating costs and predicting the process feasibility.

ABSTRAK

Asid suksinik mempunyai pelbagai kegunaan dalam pelbagai industri seperti industri makanan, farmaseutikal dan kimia. Asid suksinik secara tradisinya dihasilkan secara petrokimia. Akan tetapi, disebabkan oleh pelbagai faktor seperti kesan alam sekitar yang membimbangkan dan kos pemangkin yang mahal, kaedah biologi penghasilan asid suksinik daripada hasil fermentasi telah digunakan secara meluas. Walau bagaimanapun, kaedah biologi dalam pengeluaran asid suksinik daripada hasil fermentasi ini memerlukan kos yang tinggi. SuperPro Designer® ialah perisian yang boleh digunakan untuk menjalankan analisis ekonomi bagi proses pemulihan hiliran ini. Atas sebab itu, tujuan penyelidikan ini adalah untuk menggunakan perisian SuperPro Designer® dalam mencipta lembaran alir lengkap proses pemulihan hiliran menggunakan data awal dan kondisi daripada eksperimen-eksperimen terdahulu. Menggunakan lembaran alir yang telah dibuat, komposisi akhir asid suksinik diperolehi. Kemudian, penilaian ekonomi dijalankan untuk proses hiliran tersebut. Keputusan yang diperoleh menunjukkan bahawa 3545.07 kg/batch kristal asid suksinik dengan ketulenan 98% telah diperoleh sebagai produk akhir. Penilaian ekonomi menunjukkan hasil yang memberangsangkan kerana proses itu dianggap berdaya maju dan boleh dilaksanakan dari segi ekonomi menurut Laporan Penilaian Ekonomi (EER). Masa bayaran balik pelaburan ialah 2.88 tahun dan kos pengeluaran se-unit dianggarkan 23.40 MYR/kg. Analisis sensitiviti juga telah dijalankan dan keputusan menunjukkan bahawa proses itu masih berdaya maju pada ±25% kos proses fermentasi manakala ia menunjukkan Nilai Kini Bersih (NPV) negatif pada penurunan 25% dalam harga jualan asid suksinik. Keputusan yang ditemui dalam penyelidikan ini menunjukkan potensi penggunaan SuperPro Designer® sebagai alat simulasi dalam menganggar kos dan meramalkan kebolehlaksanaan sesebuah proses.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Material
CAGR	Compound Annual Growth Rate
EOC	Equipment Occupancy Chart
FB	Fermentation Broth
FO	Forward Osmosis
MF	Microfiltration
MYR	Malaysian Ringgit
NF	Nanofiltration
NPV	Net Present Value
PAC	Powdered Activated Carbon
PBS	Polybutyrate succinate
ROI	Return On Investment
SA	Succinic acid
TCA	Tricarboxylic acid
TEA	Techno-economic analysis
TFHF	Thin film composite hollow fiber
USD	United States Dollar

LIST OF SYMBOLS

◦C	Degree Celsius
%	Percentage
$	United States Dollar

CHAPTER 1

INTRODUCTION

1.1 Background of Study

The industrial growth that the world witness today is beyond doubt crucial in the development and modernization of any country. However, it is also inarguably one of the most important source of environmental impacts, depletion of fossil fuel and other resources, which will eventually lead to environmental deterioration (Herva et al., 2011). Petrochemical industry is classified as heavy industries in which various pollutants such as harmful air emissions, wastewater and hazardous wastes are generated (Clews, 2016). This industry is proven to be contributing to a significant share in polluting the environment. Consequently, the realization and awareness of how this concerning issue could harm the environment has led the researchers and scientists to replace petrochemical approaches with biological method (Jusoh et al., 2020).

Succinic acid, a four-carbon dicarboxylic acid is a vital precursor that has various uses in multiple industries such as food, pharmaceutical and chemical industries (Thuy & Boontawan, 2017). Other than alarming environmental impacts, other factors such as high temperature, high pressure and expensive catalysts are the reason why the attention on traditional way of producing succinic acid has been switched to the biological production and the recovery of succinic acid from the fermentation broth (Q. Li et al., 2010). However, it is a known fact that the downstream recovery process is a costly one. It is estimated that the process contributes to a major expenditure, of over 60% of the total production cost in the microbial production (Q. Li et al., 2010)

According to (Nghiem et al., 2017), in the past, there was little demand for succinic acid. In 1990, the estimation for the global production of succinic acid annually was between 16,000 and 18,000 metric tons. However, as time passes, the increasing oil prices and subsiding oil supplies have opened new opportunities in producing succinic acid from renewable sources. Moreover, succinic acid can be transformed into a number of different chemical products that are in high demand in the industrial market, such as 1,4-butanediol and other organic solvents. In the year 2020, the size and share of succinic acid market is priced at 138 million USD and it is predicted to reach a market size of 187 billion USD in 2025, at a Compound Annual Growth Rate (CAGR) of 6.2% (*Succinic Acid Market Size, Share & Trends | 2020 - 2025*, n.d.). In Europe, stricter regulations for carbon footprints that had been implemented have led the chemical industry to incorporate more applications of bio-based succinic acid in their processes. This is the main reason Europe has been the major consumer in bio-based succinic acid market, although Asia-Pacific is also nonetheless proliferating in the bio-based succinic acid market (*Bio-Based Succinic Acid Market – Global Industry Trends and Forecast to 2027 | Data Bridge Market Research*, n.d.).

SuperPro Designer® is a software that can be applied to conduct techno-economic calculations in process engineering. Processes such as batch process or continuous process can be simulated using the software. Besides that, data bases for chemicals, equipment and economical figures are also available (Bergman, 2016). The program is equipped with the specialization to provide its users with cost estimation of the process, which included capital costs, material costs, operating costs and administrative and auxiliary costs (*Intelligen, Inc*, n.d.). In this work, this software will be used to simulate the downstream recovery of succinic acid from fermentation broth by forward osmosis-assisted crystallization process and the economic evaluation will be done.

1.2 Problem statement

Apart from the harsh rivalry in the bio-succinic acid market, its high production cost is also one of the main obstacles that needs to be tackled by the researchers. The demand towards bio-based succinic acid had decreased and the major succinic acid manufacturers such as BioAmber, Myriant and Succinity GmbH had been affected directly from this issue (Choi et al., 2015). The decline in the succinic acid demand is due to its expensive cost and low efficiency of the process. According to the report "From the Sugar Platform to Biofuels and Biochemicals" published by (Dienst & Onderzoek, 2015), by 2020, the bio-succinic acid was expected to reach a market price of lower than 1,000$/tonne succinic acid with an annual revenue of approximately $539 million in order to make bio-based succinic acid competitive in the market. However, looking at the current market situation and today's production costs, this projection seems unlikely to be achieved. This implies that it is very important to reduce the operating costs and the investments in the unit equipment involved in the process.

Nevertheless, to date, the information and reported studies on process modelling and estimating the total production cost of succinic acid downstream recovery process are limited. In order to get an estimation of the process production cost and a vision of bio-based succinic acid's current situation in the market, as well as the optimization of the process flow design, a simulation model of the process needs to be studied by using an appropriate software programme.

1.3 Research objectives

The objectives of this project are:

i. To develop a process flowsheet of succinic acid downstream recovery process using SuperPro Designer® software as the simulation tool

i. To study the economic feasibility of the proposed downstream process in terms of payback time, Return On Investment and Net Present Value.

1.4 Scope of study

This research focuses on the simulation of succinic acid downstream recovery from fermentation broth by forward osmosis-assisted crystallization process. Initial data collected from previous laboratory works will be applied to SuperPro Designer® software to study the feasibility of the process design. The research is focused on the downstream recovery part, whereas the required initial data of the fermentation process was referred from various literatures. Economical evaluation of the process will be conducted and economic parameters such as payback time, Return On Investment (ROI) and Net Present Value (NPV) are being studied. Sensitivity analysis is carried out to study the impact of various economic parameters on the feasibility of the process.

1.5 Significance of study

This research is set out to study the process flow design of succinic acid downstream recovery process and the utilization of SuperPro Designer® software in evaluating the economic feasibility of the process. SuperPro Designer® is used as the simulation tool to carry out complex calculations that would be difficult to calculate or solve in real experimental setup. Besides that, the economic feasibility of the process can be studied using the software, which will reduce the cost of conducting a real experiment in a laboratory scale. On the other hand, up to this date, very limited literatures regarding the simulation study of bio-succinic acid production are available. It is hoped that with this study, the degree of information available regarding succinic acid downstream recovery can be improved. Moreover, this study can also be used to predict the economic feasibility of the process, especially in terms of profitability and proposing possible process optimizations in reducing operating costs. Furthermore, sensitivity analysis on various different parameters aids in predicting the economic performance of a process during economic fluctuations.

CHAPTER 2

LITERATURE REVIEW

2.1 Petrochemical industry and its drawbacks

The petrochemical industry is defined as a cluster of companies that are responsible in the production of organic compounds from petroleum and other types of fossil fuel (Gupta & Pathak, 2019). Products such as plastics, cosmetics, lubricants and paints are created from petrochemical commodities. As the name suggests, petrochemicals are usually produced from petroleum, even though the compounds are also can be obtained from other sources such as coal and natural gas. Approximately five percent of the yearly oil and gas supply are from petrochemical production, and this prompted more researches on renewable alternatives with less volatile pricing.

For succinic acid production, the most common petrochemical route to produce this four-carbon dicarboxylic acid is by liquid-phase maleic anhydride hydrogenation to succinic anhydride (SAN). Next, the hydration of SAN to yield succinic acid takes place. Figure 2.1-1 shows the schematic figure of the process.

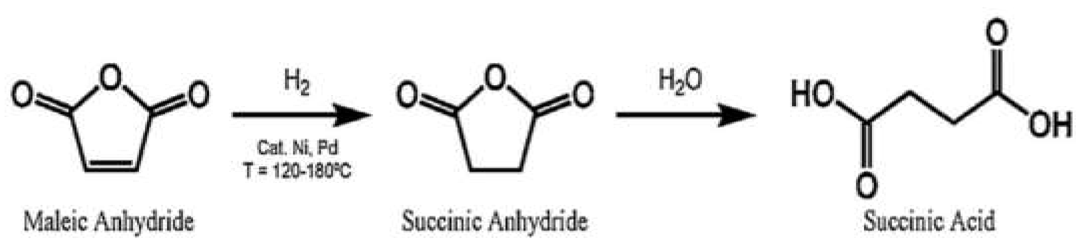

Figure 2.1-1: Schematic diagram of the two-step process of succinic acid production (Pinazo et al., 2015).

Although petrochemical method is widely used, it also carries several drawbacks. One of the most notable weakness is finite source. Fossil fuels, which are derived to petrochemicals, are limited and not renewable. Due to this reason, the petrochemical industries cannot be deemed sustainable for a long run (Pinazo et al., 2015). The limited sources will get more and more scarce as the demand towards petrochemicals is rising. As a result, the prices of petrochemical products will keep increasing due to the lesser reserves of fossil fuel.

Besides that, environmental damages are also one of the disadvantages of this industry. Burning of fossil fuels takes place in order to form petrochemical products. The combustion process results in the release of many harmful components in the air, including greenhouse gases (Takht & Saeed Sahebdelfar, n.d.). Consequently, global warming happens due to the greenhouse gases formed. Moreover, when petrochemicals are mixed with water vapor, it can cause acid rain. Last but not least, the marine life is also endangered. A considerable amount of petrochemicals spills in the sea will affect many different marine species lethally.

2.2 Switching to the production of “green” succinic acid

The declining of crude oil supply as well as the drastic increase in oil price faced by the industry has turned the global attention towards producing succinic acid biologically. Bio-based succinic acid, or in other words the “green” succinic acid is produced by making use of abundant biomass sources. As the petrochemical production of succinic acid faces multiple drawbacks, the biological method of succinic acid production is seen as a potential substitute (Ferone et al., n.d.). In this method, succinic acid is produced via fermentation and this process has drawn great interests due to its simplicity as well as being environmentally-friendly. Nevertheless, this method has its own challenges and weaknesses. Compared with petro chemically-produced succinate, the fermentation broth used in the biological method often contains low product concentration, which leads to a low recovery of the final product of succinic acid. This issue has made the “green” succinic acid production to be less competitive, especially economic-wise (Pinazo et al., 2015).

To date, various studies have been reported and this has proven the rising interest towards the bio-based succinic acid production. According to (McKinlay et al., 2007), there are multiple key challenges of the fermentative succinic acid production that has been identified and needs to be overcame. For example, the use of cost-effective carbon sources, high final product yield, little to none by-product formation and also reduction in the cost of the extraction/purification step. Furthermore, it is also very important to improve the overall process in order to make this industry economically competitive.

(Jusoh et al., 2020) stated that numerous anaerobic and facultative anaerobic microbes such as Actinobacillus succinogens, Mannheimie succiniproducens and Escherichia coli has proven their effectivity to produce succinic acid. Besides, (Pateraki et al., 2016) has previously confirmed that Actinobacillus succinogenes is one of the most prominent succinic acid producers. In their study, the FZ53 mutant strain of A. succinogenes has been reported to successfully produce the highest succinate titer using glucose, which resulted in a recovery yield of 0.82 g succinic acid per gram of glucose, and a productivity of 1.36 g L^{-1} h^{-1}. On the other hand, a study reported by (Marinho et al., 2016) demonstrated the ability of A. succinogenes to carry out co-fermentation of glucose and mannitol to produce succinic acid, using macroalgal biomass as a substrate.

Several companies that are responsible in the commercialization of bio-succinic acid includes Bioamber (2014), Myriant (2013), Reverdia (2011) and Succinity (2013) (Choi et al., 2015).

2.3 Succinic acid

Succinic acid is also named as butanedioic acid and it is a four-carbon dicarboxylic acid. The molecular formula is $C_4H_6O_4$. This acid occurs naturally in almost all animal and plant tissues. Succinic acid exists as a colorless crystalline solid and it is also water-soluble. The melting point of succinic acid is between 185-187°C (*Succinic Acid - The Chemical Company*, n.d.).

2.3.1 Succinic acid and its historical development

According to (Song & Lee, 2006), in the past, succinic acid can be primarily yielded from amber distillation process, which was the reason why this acid is called the "Spirit of Amber". Georgius Agricola was the earliest person to extract succinic acid from amber by pulverization and distillation, in the year 1546. Primarily, it was used to treat rheumatic aches and pains (*Succinic acid | chemical compound | Britannica*, n.d.). Following this event, microbial fermentation process has continued to produce succinic acid for numerous applications in the agricultural, food, and pharmaceutical sectors.

Robert Knock, a Nobel Prize winner had reported that succinic acid affects human metabolism positively and also demonstrated that when used in food industries, it shows absolutely minimal risk of acid buildup in the human body. On the other hand, succinic acid is a tricarboxylic acid (TCA) cycle intermediate as well as an anaerobic metabolism fermentation end-product.

2.3.2 Uses of succinic acid

Succinic acid has various uses in multiple industries. Amongst the most significant function of succinic acid is that it is a precursor of a variety of essential chemical compounds such as adipic acid, N-methyl pyrrolidinone, 1,4-butanediol, 2-pyrrolidinone, tetrahydrofuran, succinate salts and gamma-butyrolactone (Song & Lee, 2006).

In food production, succinic acid is used as a flavor enhancer and food ingredient. The label E363 corresponds to succinic acid and it is a natural substance that can be found in all plants and organisms. E363 is an EU-approved food additives and it is commonly used in beverages, caramels and chewing gums to regulate the acidity of the food. As a flavor enhancer, succinic acid increases the perceived saltiness and also prolongs the flavor in various sweet and savory products.

Besides that, succinic acid is also applied widely in the pharmaceutical sector. For instance, it acts as a starting material for active pharmaceutical ingredients (APIs) and also acts as additive in formulation. Moreover, it is also a useful compound that can be utilized as a cross linker in drug control release polymers.

Lastly, succinic acid is also crucial in synthesizing biodegradable polymers such as polybutyrate succinate (PBS) and polyamides (Nylon®x,4) (Willke & Vorlop, 2004) as well as being used as various green solvents (Rudner et al., 2005). Consequently, the high demand towards succinic acid is expected.

Figure 2.3.2-1 shows the succinic acid derivatives and its applications in multiple industries.

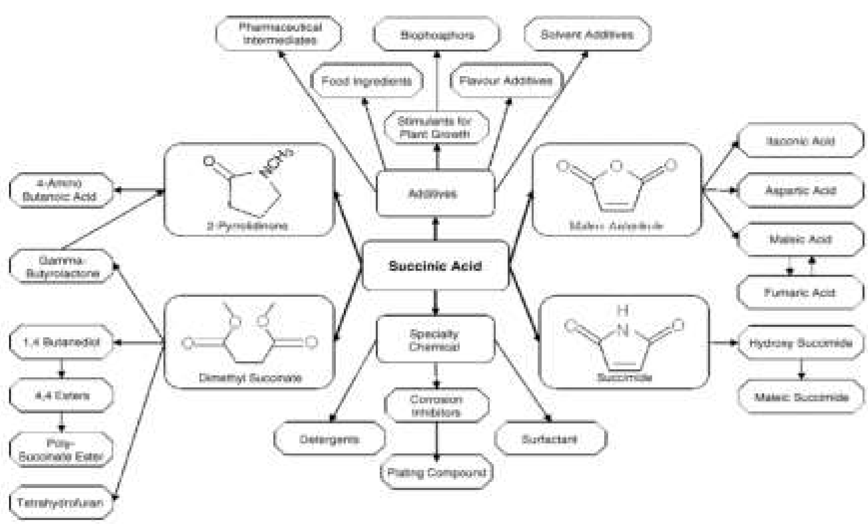

Figure 2.3.2-1: Various applications of succinic acid and its derivatives. Source: (Song & Lee, 2006)

2.3.3 The succinic acid market

In a report "Succinic Acid Market: Industry Analysis, Size, Share, Growth, Trends and Forecasts 2020-2025" reported by Market Data Forecast in February 2020, the size and share of succinic acid market has achieved a value of USD 138 million in the year 2020. With a Compound Annual Growth Rate (CAGR) of 6.2%, it is expected to grow to a higher market value of USD 187 billion by the year 2025 (*Succinic Acid Market Size, Share & Trends | 2020 - 2025*, n.d.).

When the global pandemic hit the population of the world, a surge in food deliveries has led to the rising of the packaging industry. This is a significant indicator that the succinic acid industry is currently expanding. On the contrary, succinic acid market is also encountering some challenges as the energy prices keeps increasing and more competitors of succinic acid substitutes are being continuously developed and introduced.

2.4 Downstream processing of succinic acid

Multiple studies regarding the downstream recovery of succinic acid has been published to date. The succinic acid producers that are currently being used includes Actinobacillus succinogenes, Anaerobiospirillum succiniciproducens, Corynebacterium glutamicum, Mannheimia succiniciproducens and some modified yeast. Sugar, glycerol as well as waste biomass are the examples of the substrates that are used to produce succinic acid through downstream process. In succinate fermentation process, different by-products are obtained when different species of producers are involved (Cheng et al., 2012).

The general procedure to produce bio-based succinic acid through downstream processing commonly involves product recovery, concentration, acidification and final purification step. Numerous methods for recovering succinic acid from fermentation broth have been discovered. For instance, crystallization, solvent extraction, precipitation, electrodialysis, chromatography and membrane separation (Sun et al., 2019).

One of the most common methods for recovering succinate from the fermentation broth is calcium precipitation. Calcium hydroxide, $Ca(OH)_2$ is added in an excess amount to stimulate succinate precipitation. However, this process produces a large amount of $CaSO_4$ as a by-product which leads to a final succinic acid product with relatively low purity, as confirmed by (Huh et al., 2006). A research conducted by (Cheng et al., 2012) that involves calcium precipitation step in their process has reported a succinic acid yield of 75% and 28% from simulated and real fermentation broth, respectively.

The process of one-step recovery of succinic acid by direct crystallization had been studied by (Q. Li et al., 2010). In this process, the fermentation broth is acidified to pH 2 and cooled to a temperature of 4◦C at the end of the fed batch fermentation and approximately 70% succinic acid was recovered from the fermentation broth. (Sze et al., 2014) had studied on the direct crystallization method by using Actinobacillus succinogenes strain on wheat-derived hydrolysate. As a result, very high purity of final product was achieved, at a soaring 99% while 89.5% of recovery yield was obtained.

On the other hand, (Omwene et al., 2020) recently studied a system combining ultrafiltration, vacuum distillation and reactive extraction to separate succinic acid from the real fermentation broth that also contains other carboxylic acids. The results obtained from this study showed that the pKa of acid and the pH of the aqueous phase have a strong influence towards the reactive extraction of organic acids from fermentation broth.

(Sosa et al., 2016) had incorporated a three step membrane process in their study, which includes electrodialysis, nanofiltration and Donnan dialysis by using carob pod-based fermentation broth in the recovery process. Membrane fouling and reduced fluxes had been noted although 90% of succinate rejection was achieved. (Thuy & Boontawan, 2017) has reported a process that integrates microfiltration (MF), nanofiltration (NF) and crystallization in order to recover succinic acid. Notable results are obtained as a final purity of 99.18% of succinic acid is achieved. However, it is quite noteworthy that the process consumes a high amount of water throughout the process, especially during diananofiltration mode.

Continuous researches on new and improved separation technologies will lead to a better outcome in recovering succinic acid efficiently. Numerous unit processes can be integrated in one downstream recovery process in order to achieve better product recovery (Law & Mohammad, 2018).

2.5 Recovery of succinic acid from fermentation broth by forward osmosis-assisted crystallization process

Dewatering fermentation broth is critical for a process's overall energy economy, especially when a high-energy separation step like distillation is required. Thus, forward osmosis has prominent strengths compared to the other existing concentration and water removal methods (Law & Mohammad, 2018). It consumes less energy and has minimal membrane fouling.

In the study performed by (Law et al., 2019), the steps involved in the downstream recovery process is fermentation, centrifugation, activated carbon treatment, forward osmosis, acidification, crystallization and filtration/ drying.

2.5.1 Fermentation broth

Fermentation broth is defined as a complex solution where it acts as a medium and provide nutrients for the microorganisms to grow and reproduce, which will result in numerous fermentation products. Besides that, physical and biochemical processes also take place in the fermentation broth.

2.5.2 Activated carbon treatment

Powder activated carbon (PAC), also known as pulverized activated carbon, is defined as small activated carbon particles. It is formed through the pulverization process of activated carbon and normally has a size of 0.075mm or smaller. (*Powder activated carbon (PAC) | Desotec*, n.d.)

According to the American Society for Testing and Material or currently known as ASTM International, activated carbon particles with a size of 0.18 mm or smaller are classified as PAC. They have also established the following differentiation:

- Powdered activated carbon is defined as particles that have less than 0.045mm of mean particle diameter; whereas
- Fine mesh is defined as particles that are sized in a range of 0.045 and 0.180mm of mean particle diameter

Due to the fact that the pretreatment or clarification of fermentation broth is very crucial in downstream recovery processes, various methods such as membrane-based process are being applied. However, the challenge of incorporating membrane-based method such as ultrafiltration and microfiltration in the process is membrane fouling propensity. So, for the purpose of eliminating impurities from the fermentation broth and prevent membrane fouling, activated carbon adsorption could be effective. It is also a reliable and economical method.

However, (Q. Li et al., 2010) stated that there is only a small number of studies that have been reported regarding the removal of impurities from fermentation broth by activated carbon treatment.

2.5.3 Forward osmosis

Forward osmosis (FO) is a low energy process that works by having two solutions with different concentrations or osmotic pressures. Similarly with reverse osmosis (RO), selectively permeable membrane is used to separate the solution (Nicoll, 2013).

In forward osmosis, the concentration of feed water solution occurs at one side of the membrane while the dilution of the draw solution takes place at the other side. This will decrease the differential osmotic pressure and the solvent will flow. In processes that apply forward osmosis technology, water flux and reverse solute flux are commonly studied in order to examine the effectivity of forward osmosis.

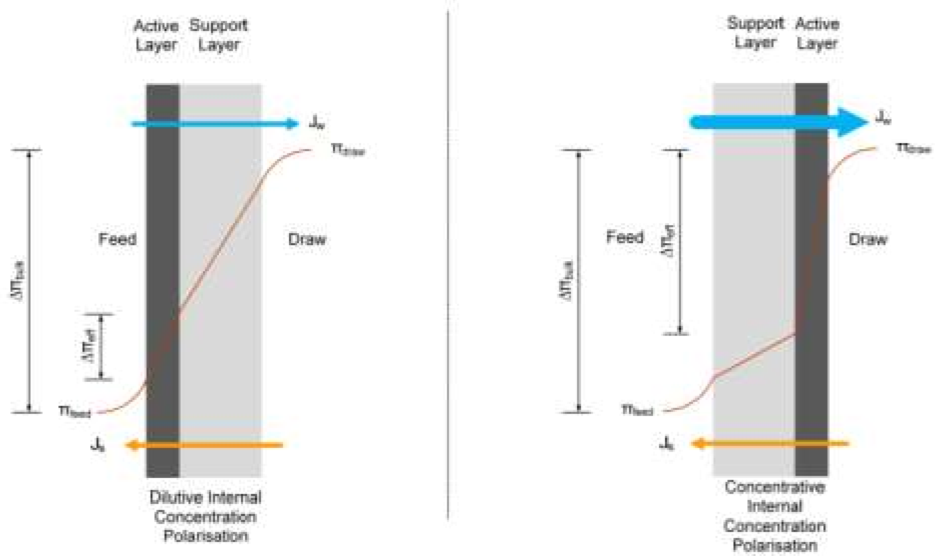

Figure 2.5.3-1: Schematic diagram of dilutive and internal polarization concentration process (Nicoll, 2013)

Several studies have been published to date on processes that have applied forward osmosis technology in the recovery of organic acids through downstream process. For instance, (Law & Mohammad, 2018) has studied the FO performance in separating and concentrating succinic acid from its fermentation broth. This process used real sea water as the draw solution and 67 g/L of succinic acid. The influence of the feed solution pH is evaluated.

In a study conducted by (Ruprakobkit et al., 2019), the effect of the operating parameters on FO process performance is evaluated by sensitivity analysis, where two systems of a single organic acid (acetic acid) and a mixture of two organic acids (acetic acid and butyric acid) were being studied. 1M of ammonium chloride, NH_4Cl was used as the draw solution. From the simulation results obtained, the sensitivity analysis demonstrated the influence of the rate of rejection and concentration performance to the process, as well as the cost of construction and system modification of the overall process.

Recently, (Garcia-Aguirre et al., 2020) had done a study to investigate the performance of FO technology in the concentration of succinic acid, lactic acid and ethanol from their respective fermentation broths. A thin film composite hollow fiber (TFHF) membrane was used when FO was applied to the fermentation broths, that were previously treated. This study had reported a noteworthy results of succinic acid fermentation by using 5.0M of NaCl as the draw solution. Final succinic acid titer of 186.7 ± 9.3 gL^{-1} is obtained and 85% of water is successfully removed.

2.5.4 Crystallization

According to Cambridge Dictionary, crystallization means the process of turning into crystals. Moreover, (*Crystallization*, n.d.) stated that during the process, the formation of solid, namely crystal takes place when the atoms or molecules are organized. Crystallization occurs when a solution is supersaturated. The supersaturation state can be achieved by lowering the solubility of a solution, for example through cooling process. Besides that, when a solvent is removed from a solution through evaporation, it can also create supersaturation (García-Fernández et al., 2015: Anisi et al., 2016). Crystals can be formed into many shapes, such as cubic, tetragonal, orthorhombic and many more.

(Drioli et al., 2012) stated that in the chemical and pharmaceutical sectors, crystallization is one of the most commonly used separation process and it has been applied in the industries since years ago. Furthermore, crystallization had also proven its high ability in obtaining high purity product, thus confirming the fact that this process can be regarded as a positive approach in the separation of solid-liquid mixtures, as well as the final recovery of organic product (Thuy et al., 2017).

2.6 SuperPro Designer® Software

Process simulation software that is currently being widely applied in petroleum and chemical sectors, is a series of computer algorithms that is able to conduct a mathematical modelling of the performance of individual unit operations that are involved in a particular process. Multiple biological, chemical, and physical processes may be represented in each model. For most of the software programs, it provides the users with information from their databases of equipment and material properties.

Techno-economic analysis (TEA) is important in order to determine the feasibility of a project. TEA usually combines process modelling, engineering design and economic evaluation. This can be accomplished by assessing a process's economic feasibility and identifying any cost-risk aspects during the planning and implementation stages. The most common software products that are being used are ASPEN Plus®, Microsoft EXCEL® and SuperPro Designer®. Each of the software has their own strengths and weaknesses.

Although Microsoft EXCEL® is easily accessible and user-friendly, the analysis that can be done is only limited to a small number of unit procedures. This is because the calculations for the process analysis is done using spreadsheets that is provided by the programme. On the other hand, ASPEN Plus® enables their users to conduct process optimization and it requires a large amount of technical information. However, the downside of this software program is that the downstream and economic analysis of large-scale processes is limited, which will reduce the accuracy of the final results.

SuperPro Designer® is a process simulation software that is capable to model, evaluate and optimize processes, especially bioprocesses. It was developed to simulate unit operations in a batch or continuous processes. Moreover, the software is also well-equipped with advanced features to facilitate various calculations such as mass and energy balances as well as having a big database to store data needed for the simulation such as chemical component and mixtures, equipment and resources. This software is user-friendly and can easily be used by non-experts to carry out techno-economic analysis of a particular process (Bergman, 2016).

Various reports on the simulation study of bio-based products recovery by using SuperPro Designer® software had been reported to date. For example, in a research carried out by (Phanthumchinda et al., 2018), the yearly production of 100,000 kg of lactic acid is being simulated using the software to determine the investment and operating cost for the plant. This research proposed a membrane-based process design and the results obtained showed that more unit operations lead to a higher production cost of the process. On the other hand, the implementation of in-parallel integrated brackish water reverse-osmosis technology is found to be effective in minimizing the process operating cost by 23-31%.

Other than that, (Harun et al., 2019) carried out a research on simulating an anaerobic digestion process to produce biogas by treating food waste. The simulation is done using SuperPro Designer® software. In order to determine the impact of food waste-to-water ratio and hydraulic retention time on methane production, a sensitivity analysis has been performed on the simulation results. The simulation findings demonstrated that increasing HRT enhanced the methane composition of biogas because more time was available for microorganism activities to produce biogas.

Last but not least, most recently, with the aim to analyze the commercialization of bio-based succinic acid techno-economically, a case study of BioAmber's carbohydrate-based succinic acid was conducted by (X. Li & Mupondwa, 2021). SuperPro® Designer software was used to design and simulate a yearly output of 30,000 tonnes of bio-succinic acid in a production plant. The study found out that succinic acid costs $2.23 per kilogram, which was significantly more than BioAmber's initial estimation. Under current succinic acid prices, derived coproducts such as 1,4-butanediol would not be economical, according to the sensitivity analysis done in the simulation study.

Table 2.6-1 summarizes the previous reported simulation studies of several bio-based process by using SuperPro Designer ® software.

Table 2.6-1: Reported simulation studies of several bio-based process

Process	Aim	Findings	References
Lactic acid downstream recovery	To determine the investment and operating cost for lactic acid production plant.	- High number of unit operations influenced the production cost - By using in-parallel integrated brackish water RO membrane units, the operating cost is reduced by 23-31%.	Phanthumchinda et al., 2018
Biogas production by anaerobic digestion	To determine the impact of food waste-to-water ratio and hydraulic retention time on methane production	- Increasing HRT enhanced the methane composition of biogas because more time was available for microorganism activities to produce biogas.	Harun et al., 2019
Case study of BioAmber's carbohydrate-based succinic acid production plant	To assess the commercialization of bio-based succinic acid	- The unit cost of succinic acid was \$2.23 kg^{-1}, which was much more expensive than BioAmber's original projection	X. Li & Mupondwa, 2021

2.7 Economic Assessment

2.7.1 Capital cost

Capital cost for a chemical plant generally includes purchase price of the equipment, delivery and installation of the equipment, construction site remediation and design, labor of contractors and construction workers as well as any other costs that comes with building a chemical plant. It is very crucial to calculate the capital cost in order to assess a chemical process's overall economic feasibility.

There are a variety of sources to gather accurate and up-to-date information about the capital cost, such as catalogues, cost estimation software, estimation of total cost based on the cost of components and also cost correlations (*IHS CHEMICAL Chemical Industry Capital Costs: A Global Spending Outlook Special Report Prospectus IHS Chemical Prospectus IHS CHEMICAL 2*, 2015).

2.7.2 Operation cost

Operating costs are the costs incurred in order to ensure that the company's daily operations are maintained smoothly (Khalid, 2015). These include operating expenses such as inventory, rent, equipment maintenance, insurances, marketing and other overhead costs. Operating cost also includes the direct costs of goods sold (COGS) but it excludes non-operating financial expenses including interest, investments, or foreign currency translation. (*Operating Cost Definition*, n.d.). The operating cost is basically defined as the sum of operating expenses and the costs of goods sold.

CHAPTER 3

METHODOLOGY

3.1 Materials

In this project, SuperPro Designer® software (Intelligen Inc.) is downloaded and installed in the computer to study the process flow design of downstream recovery of succinic acid production. All initial data are gathered from previous laboratory works and literatures.

3.2 Equipment

Personal computer will be used to carry out this simulation study.

3.3 Flow chart

Figure 3.3-1 shows the overall flow chart for the simulation study.

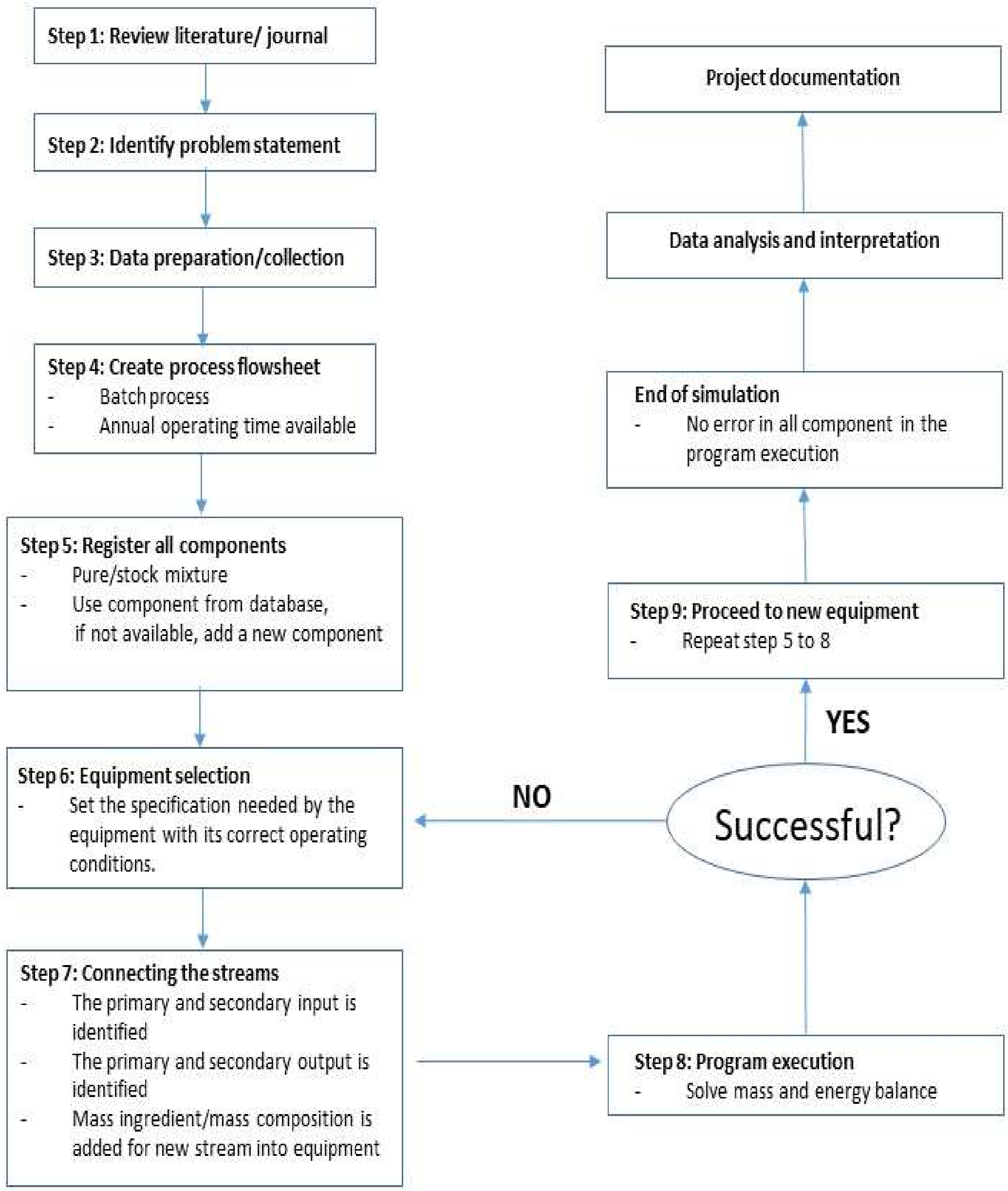

Figure 3.3-1: Overall flowchart of the study

The first step is to review various literatures and journal to gain more detailed information and knowledge on the downstream process. Secondly, the problem statement for this project is identified. Then, data is gathered and collected from previous experimental works as a starting point for the simulation study. Once all the necessary data is collected, the process flowsheet will be created in the program. In this study, a batch process of succinic acid downstream recovery is being simulated.

3.4 Initial Setup

Once the software programmed is launched, the operating mode for the process is set. Figure 3.4-1 below shows the dialog box for the initial setup of the process. Batch process was selected as the operating mode and the annual operating time for the process was set to be 7920 hours, which is the default value given by the software and is also widely used in various literatures.

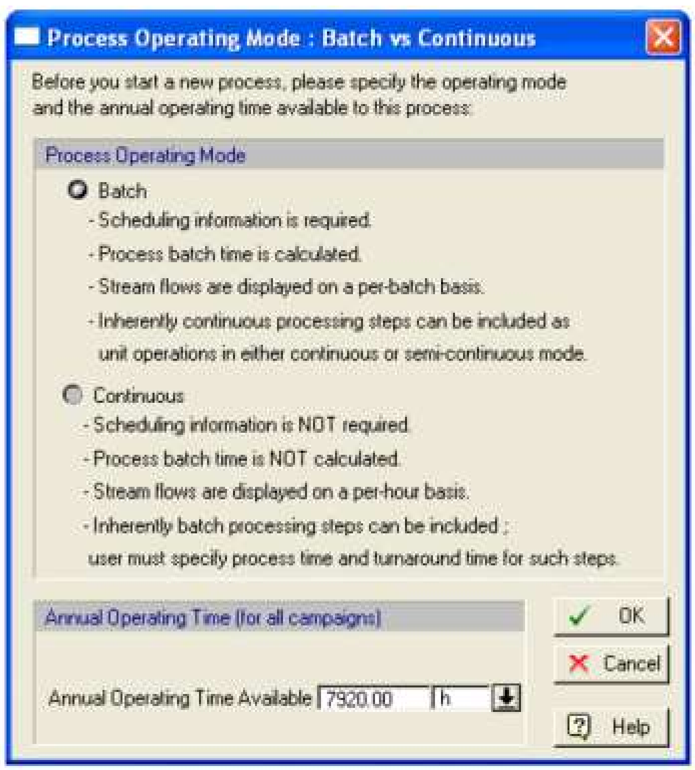

Figure 3.4-1: Program operating mode setup

After setting up the operating mode for the process, a complete flowsheet of the process had been created. The process that will be studied in this project is a downstream recovery process of succinic acid from fermentation broth by forward osmosis-assisted crystallization previously studied by (Law et al., 2019). Mainly, the process is divided into eight main sections. It consists of fermentation, centrifugation, activated carbon treatment, filtration, forward osmosis, acidification, crystallization and finally drying. Figure 3.4-2 summarizes the flow diagram of all the steps involved in the downstream recovery of bio-based succinic acid.

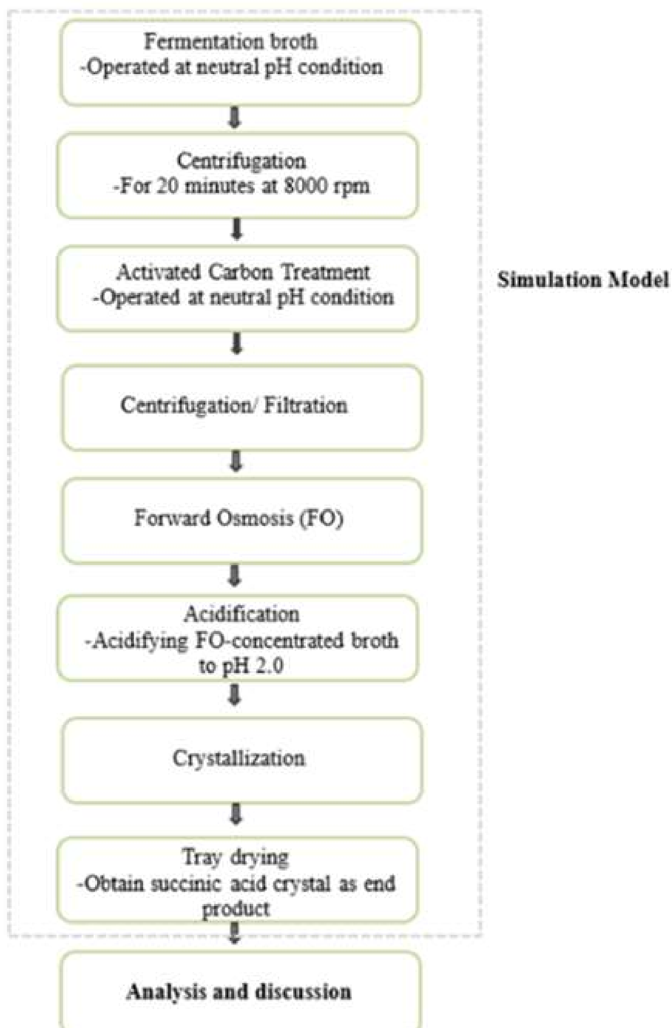

Figure 3.4-2: Flow diagram of succinic acid downstream recovery (Law et al., 2019).

The operating data applied were from the previous results obtained in experiments using laboratory-scale apparatus. The process is a batch process and the experiment is carried out at room temperature, (25 ± 2 ◦C) and pH 6.8. As can be seen in Figure 3.4-2, the process started with the collection of fermentation broth from the supplier and then the collected fermentation broth went through a centrifugation step for 20 minutes at 8000 rpm. This step is done to separate the cell biomass and macromolecules from the broth. After that, activated carbon adsorption was selected as a pretreatment step for this process to remove residues such as glucose and impurities. The presence of these impurities contributes to the dark color of fermentation broth, which will consequently reduce the purity of the final succinic acid crystals (Thuy & Boontawan, 2017). Next, in order to remove the residual activated carbon, centrifugation once again took place and consecutively the pre-treated broth was filtered through vacuum filtration to separate any suspended residues from the broth. Forward osmosis (FO) was selected as the concentration step in this work. Then, the broth that has been up-concentrated through FO was adjusted to pH 2 through acidification process. Finally, succinic acid was crystallized and dried in a tray dryer to obtain succinic acid crystals as the final product.

3.5 Components and Mixtures Registration

The next step is to register all components and mixtures that are involved in the process. Figure 3.5-1 shows the dialog box for components registration, which showed all of the pure components used in this simulation.

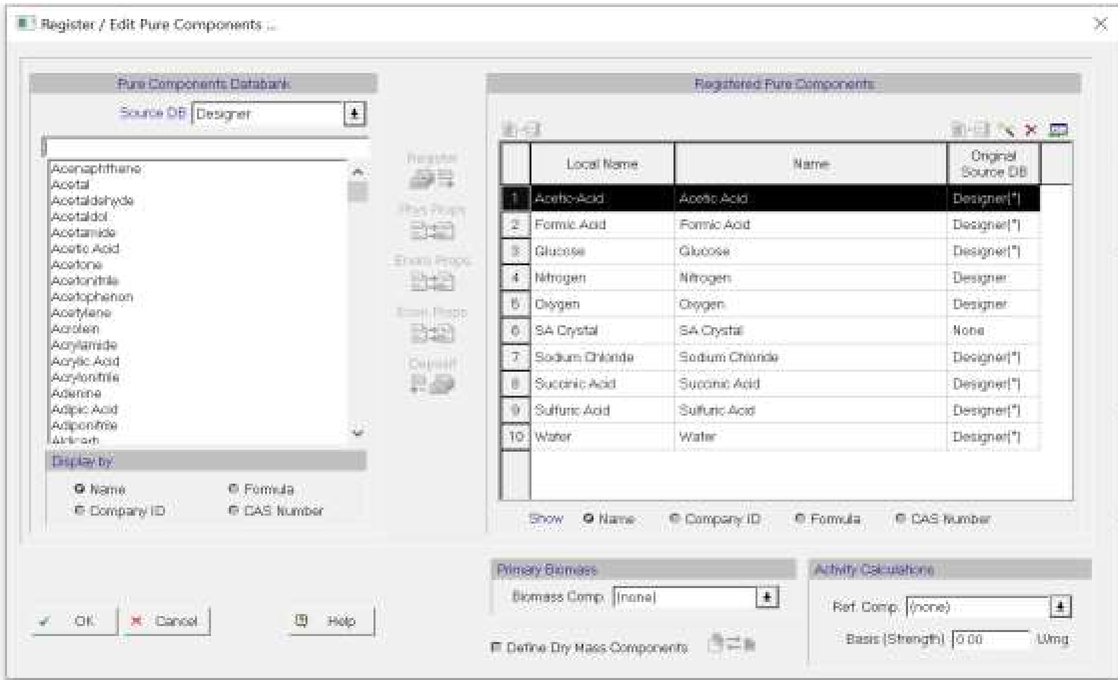

Figure 3.5-1: Dialog box for component registration

Besides that, stock mixtures were also registered. The mixtures involved in this process includes fermentation broth as a starting material, sulfuric acid (H_2SO_4) for acidification step, sodium chloride solution (NaCl) as a draw solution in forward osmosis, and air. Table 3.5-1 below shows the initial composition of fermentation broth, referred from the laboratory works done by (Law et al., 2019).

Table 3.5-1: Properties and concentrations of main components present in the fermentation broth

Component	**Molecular formula**	**Molecular weight (D_A)**	**pK$_A$**	**Concentration (g/L)**
Succinic acid	$C_4H_6O_6$	118.09	4.21; 5.64	29.16 ± 0.9
Acetic acid	$C_2H_4O_2$	60.05	4.7	3.74 ± 0.37
Formic acid	CH_2O_2	46.03	3.84	0.25 ± 0.04
Glucose	$C_6H_{12}O_6$	180.16	-	3.35 ± 0.3

In SuperPro Designer®, the properties of the component and mixtures are provided in the program's databank, drawn from multiple source databases. Besides that, in order to carry out economic evaluation, the purchasing prices of the raw materials, as well as the selling price of the final product were registered. For this study, the prices of raw materials used are the default values provided by the databank, using 2021 as the year of analysis. The cost of obtaining the fermentation broth was referred from (Bukhari et al., 2019). Meanwhile, the selling price of succinic acid crystals is referred to the current market and also previous studies (X. Li & Mupondwa, 2021). The currency used in this study is Malaysian Ringgit (MYR) and United States Dollar (USD).

3.6 Unit procedures

After all components and mixtures have been registered, the process flowsheet was developed by adding unit procedures according to its order. To add a unit procedure, the desired unit procedure will be selected from the Unit Procedures Menu Box. Example is shown in figure 3.6-1.

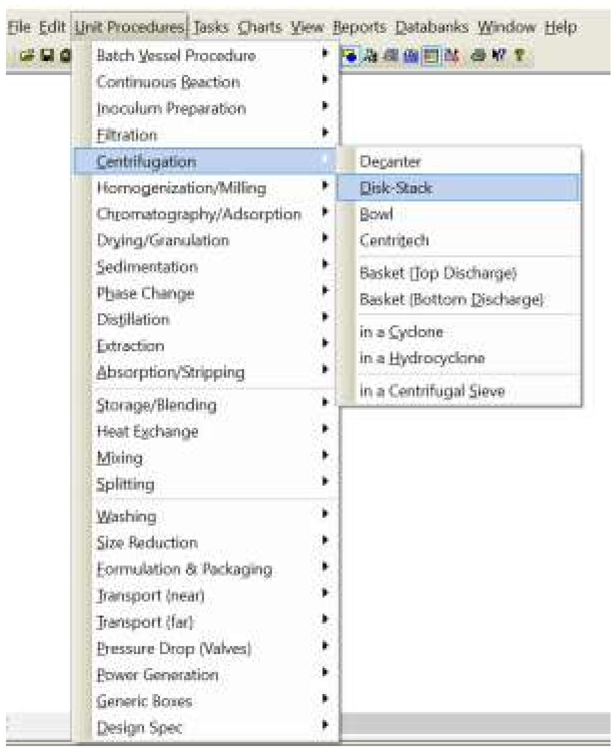

Figure 3.6-1: Unit Procedures dialog box.

Then, after the correct unit procedure is added to the flowsheet, streams will be added. Generally, the streams consist of three types, feed streams, intermediate streams and product streams. To add the streams to the flowsheet, Connect Mode will be activated on the Main toolbar, and all streams will be added to the unit procedure one by one. Once a unit procedure is placed in the flowsheet and all the required procedure data as well as the operations involved in each equipment are being introduced successfully, material and energy balances were conducted.

3.6.1 Centrifugation

Firstly, the collected fermentation broth was centrifuged for 20 minutes at 8000 rpm. Cell biomass and macromolecules present in the broth were removed in this step. In this study, a disc-stack centrifuge was used. Fermentation broth enters the centrifuge with a mass flow of 10000 kg FB/batch at a temperature of 25℃ and pressure of 1.013 bar.

3.6.2 Activated carbon treatment

Broth decolorization is crucial in order to obtain a final product with high purity. Besides that, this pretreatment step is also beneficial in reducing the contamination tendency of SA crystals (Thuy & Boontawan, 2017). A granulated adsorption column for liquid streams was proposed in this study, where granular activated carbon is used as default absorbent. This adsorption unit resembles the function of a packed bed adsorption column (Nieto et al., 2020). Residual glucose and coloring impurities are removed in this pretreatment step.

3.6.3 Centrifugation and filtration

After the pretreatment step, the broth is centrifuged by a disk-stack centrifuge to remove the activated carbon. Then, the pretreated broth filtered through vacuum filtration to ensure that all suspended residues are removed from the broth. Rotary vacuum filter with a cake porosity of 0.4 v/v is selected as the unit operation for the filtration step.

3.6.4 Forward Osmosis (FO)

FO was selected as the concentration step in this downstream recovery process (Law et al., 2019). 5M NaCl was employed as the draw solution (DS) to induce osmotic pressure driving force for FO. One of the reasons NaCl was chosen is because of its reasonable cost as well as being nontoxic. Besides that, the osmotic pressure difference between feed solution and DS can be increased thanks to the high concentration of DS, and thus enables a high water flux.

However, SuperPro Designer® software is not equipped with a built-in design of a FO cell. Thus, the unit procedure of a FO process was custom-designed using the generic module option (Nieto et al., 2020). Both feed solution and DS were circulated in a closed loop counter-current mode (Law et al., 2019).

3.6.5 Acidification

Sulfuric acid (H_2SO_4) is used in this study to adjust the pH of the fermentation broth to 2.0. This step is important according to (Q. Li et al., 2010) because in an acidic condition where pH is much lower than the pK_a value, succinic acid molecules are commonly found in the undissociated free acid form. As a result, succinic acid will be less soluble and supersaturation of succinic acid solution can be achieved easier with optimum cooling temperature, and consequently will result in a more effective crystallization process (López-Garzón & Straathof, 2014). Acidification process took place in a blending tank at 25℃ and 10.0132 bar.

3.6.6 Crystallization

In this study, the final product is obtained through direct crystallization as it is one of the classical method to recover succinic acid produced by fermentation process. Crystallization took place in a continuous crystallizer with a crystallization yield of 98%. The crystallization temperature introduced for this process is 4℃.

3.6.7 Drying

When the succinic acid has been crystallized, the succinic acid crystals were dried in a tray dryer to obtain anhydrous succinic acid crystals with a final temperature of 50℃.

3.7 Economic Evaluation

Once the material and energy balances are successfully achieved from the process flowsheet, a comprehensive economic analysis had been carried out using SuperPro Designer® software. The software estimated the purchasing prices of raw materials and major equipment for the year 2021. Economic evaluation report can be generated from the software, as shown in an example in Figure 3.7-1 below.

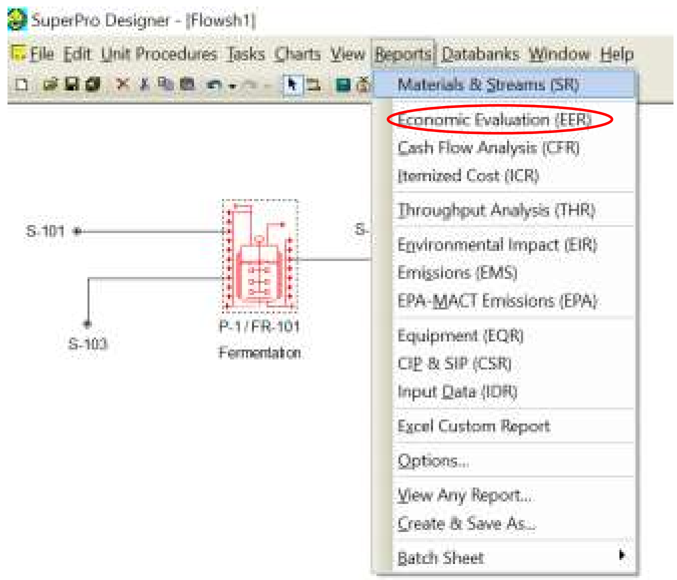

Figure 3.7-1: Reports dialog box

The software calculated the total capital investments and operating costs for the process. The results from this calculation are reflected in the Executive Summary for the project.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Process Simulation

The process simulation is set up using SuperPro Designer® software where all initial data and unit procedure had been explained in Chapter 3. Figure 4.1-1 below shows the complete flowsheet of the simulated downstream processing of succinic acid production. There are eight unit procedures and 22 streams involved in the process. In order to carry out this simulation, it is assumed that a total mass flow of 10000 kg/batch of fermentation broth enter the centrifuge (DS-101) and at the end of every batch, a total of 3545.07 kg of succinic acid crystals with a purity of 98% are obtained at the tray dryer (TDR-101). Scheduling, equipment occupancy and economic evaluation were carried out after all material and energy balances were successfully verified. The year of analysis for the economic evaluation is 2021 and the production plant is assumed to have a lifetime of 15 years and 7920 annual exploitations.

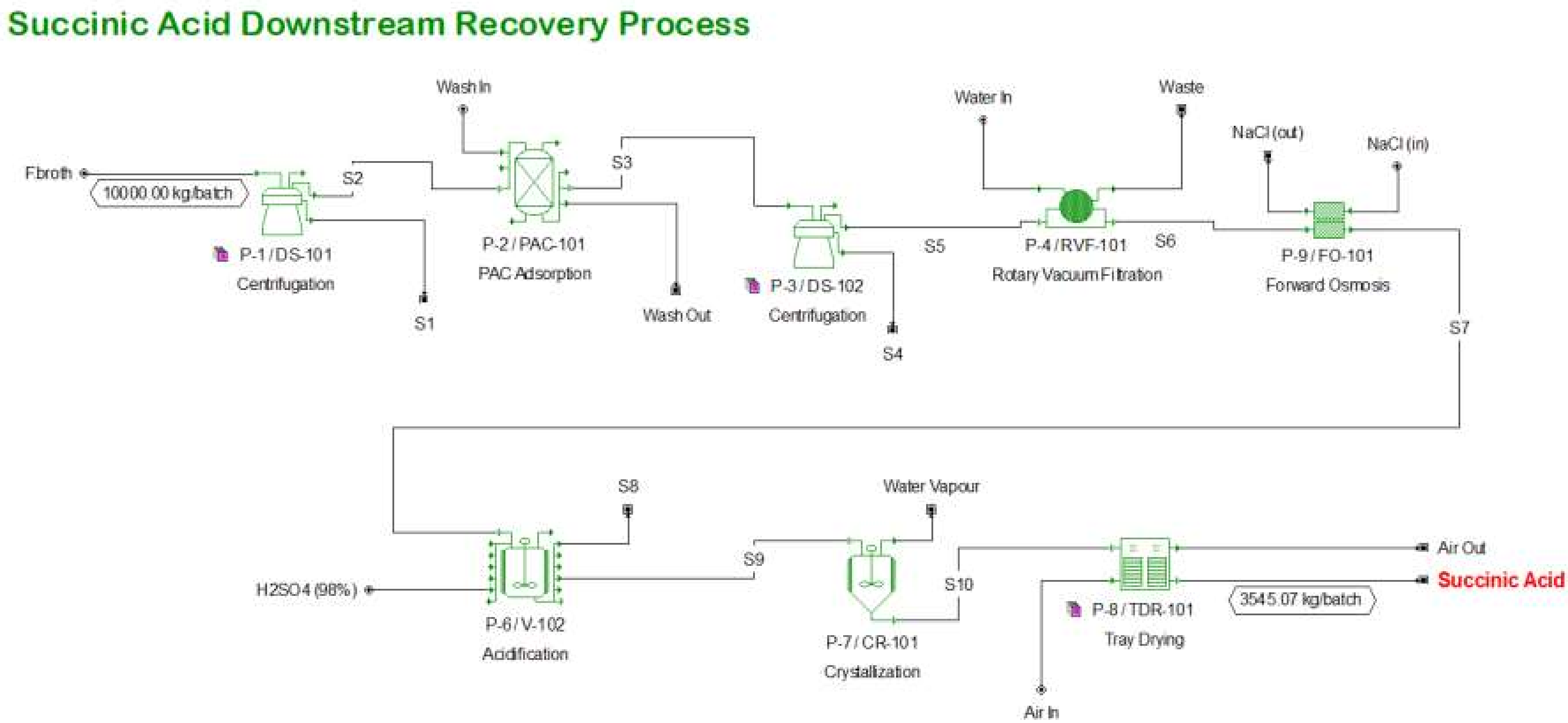

Figure 4.1-1: Succinic acid downstream recovery simulation using SuperPro Designer® Software.

As can be seen in the complete flowsheet of the process as portrayed in Figure 4.1-1, the downstream process started when the collected fermentation broth (10000 kg/batch) entered the disk-stack centrifuge (DS-101), then the broth is pretreated in a PAC adsorption column (PAC-101). After that, the pretreated FB is centrifuged (DS-102) and filtered (RVF-101) once again to remove suspended residues. Forward osmosis took place in a custom-designed generic box (FO-101) because a built-in unit procedure for FO is not available in the software. Next, acidification of the broth took place in a blending tank (V-102) and after that, succinic acid was crystallized in a continuous crystallizer (CR-101) where SA crystals are obtained and finally dried in a tray dryer (TDR-101) to obtain the final product of SA with a purity of 98%. This purity value was selected after thorough comparison on multiple bio-succinic acid catalogues in the current market and it was found that majority of the existent bio-succinic acid manufacturers sell the acid at a purity of >98% (Sharma et al., 2020). Table 4.1-1 summarizes the unit procedures simulated in the flowsheet and its quantity.

Table 4.1-1: Unit procedures.

Unit Procedure	**ID**	**Quantity**
Centrifuge	DS-101 DS-102	2
PAC Column	PAC-101	1
Rotary Vacuum Filtration	RVF-101	1
Blending Tank	V-102	1
Crystallizer	CR-101	1
Tray Dryer	TDR-101	1
Total		1

Material and energy balances are carried out in the simulation. Table 4.1-2 summarizes the total mass flow, temperature, pressure and enthalpy of every stream simulated in the flowsheet.

Table 4.1-2: Streams summary.

Stream	F.broth	S1	S2	S3	Wash In
Total mass flow (kg/batch)	10000	689.7	9310.3	8516.5	27.9
Pressure (bar)	1.013	1.013	1.013	1.013	1.013
Temperature (◦C)	25	40.7	40.7	40.7	25
Enthalpy (kWh/batch)	199.03	22.03	301.81	283.98	0.82
Stream	**Wash Out**	**S4**	**S5**	**Water In**	**Waste**
Total mass flow (kg/batch)	821.7	12.4	8504.1	100	22.8
Pressure (bar)	1.013	1.013	1.013	1.013	1.013
Temperature (◦C)	39.6	56.1	56.1	25	39.1
Enthalpy (kWh/batch)	18.65	0.55	390.25	2.92	0.70
Stream	**S6**	**S7**	**NaCl (5M) in**	**NaCl(5M) out**	**H2SO4 (98%)**
Total mass flow (kg/batch)	8581.3	8581.3	34.4	34.4	100
Pressure (bar)	1.013	1.013	1.013	1.013	1.013
Temperature (◦C)	55.6	55.6	25	25	25
Enthalpy (kWh/batch)	392.5	392.47	0.89	0.89	1.02
Stream	**S8**	**S9**	**S10**	**Water Vapour**	**Air In**
Total mass flow (kg/batch)	97.9	8154.2	6337.1	1817.1	100
Pressure (bar)	1095	10.5	10.5	10.5	1.013
Temperature (◦C)	55.4	55.4	4	181.2	25
Enthalpy (kWh/batch)	2.14	371.7	18.43	1463.77	0.7
Stream	**Air Out**	**Succinic Acid**			
Total mass flow (kg/batch)	2892	3545.07			
Pressure (bar)	1.013	1.013			
Temperature (◦C)	50	50			
Enthalpy (kWh/batch)	1460.37	97.46			

As seen in Table 4.1-2, 3545.07 kg/batch of succinic acid crystals are obtained as the final product in tray dryer. The purity of the crystals was set to be 98% and the yield can be calculated by using Eq.4.1-1 below, where W_{SA} is the dry weight of SA crystals recovered and W_0 is the initial dry weight of SA in fermentation broth (Law et al., 2019). The initial dry weight of SA in the fermentation broth (W_0) in this case is 4000 kg. The yield of SA crystals is 89%. The calculation of yield can be found in Appendix A.

$$Yield\ (\%) = \left(\frac{W_{SA}}{W_0}\right) x\ 100\% \qquad \text{Eq. 4.1-1}$$

From the overall process flowsheet that has been created and the mass and energy balances that have been achieved, the composition of every streams are noted and tabulated (Table 4.1-2). These values are important in order to conduct the economic evaluation of the process, which was carried out in the next section. The amount of succinic acid produced as the final product at the stream “Succinic Acid” was used as the main revenue (selling product) for this production plant.

4.2 Process Scheduling

In batch processes, process scheduling deals with the timing of operations. In SuperPro Designer®, the users can specify the starting times and durations of every operation. Besides that, users can also view the resulting schedule for either a single batch or multiple batches in a single product campaign. The software is capable to detect any scheduling conflicts in the simulation, such as equipment sharing violations and resource consumption violation. Thus, this will help the users to visualize the problematic part in the simulation and propose a solution to avoid the error.

Recipe Scheduling Information dialog box shows the key process scheduling data that is involved in the simulation. It can be found on the Recipe Scheduling Information on the Tasks menu, as shown in Figure 4.2-1 below. The dialog box shows that the overall Batch Time for this process is 61.73 hours. This means that it takes 61.73 hours from the start of a given batch until the end of that same batch, in which the pure final product is produced. Other than that, it is also indicated from the recipe that Tray Dryer (TDR-101) was the unit procedure with the longest duration, which took 28.13 hours to complete. The long duration of this procedure is to ensure that the SA crystals are completely dried at the end of the production. The overall Recipe Cycle Time, which is the time between consecutive batches, is 28.13 hours.

Meanwhile, Equipment Occupancy Chart (EOC) reflects the information on how various operations are being executed as a function of time. This chart can be represented for a single or multiple batches, with different colors assigned for every batch. Each single-colored bar in the chart represents the procedure execution over time in a specific equipment for a given batch. Using this chart, users can easily visualize time bottlenecks. The EOC for this simulation is shown in Figure 4.2-2. From the chart, it is proven that TDR-101 is the bottleneck since it has the least idle time between consecutive batches. This means that a delay or problem in the Tray Dryer will result in a delay of the overall acid production.

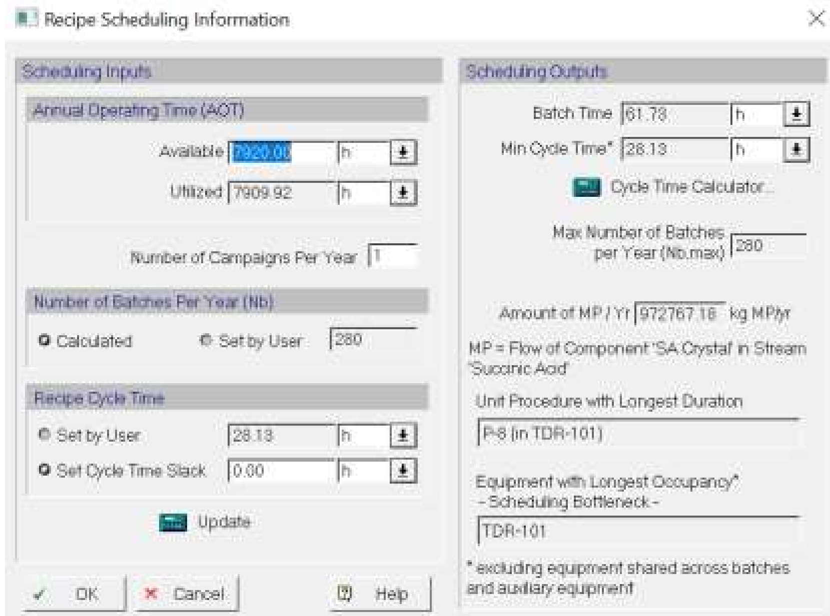

Figure 4.2-1: Recipe Scheduling Information dialog.

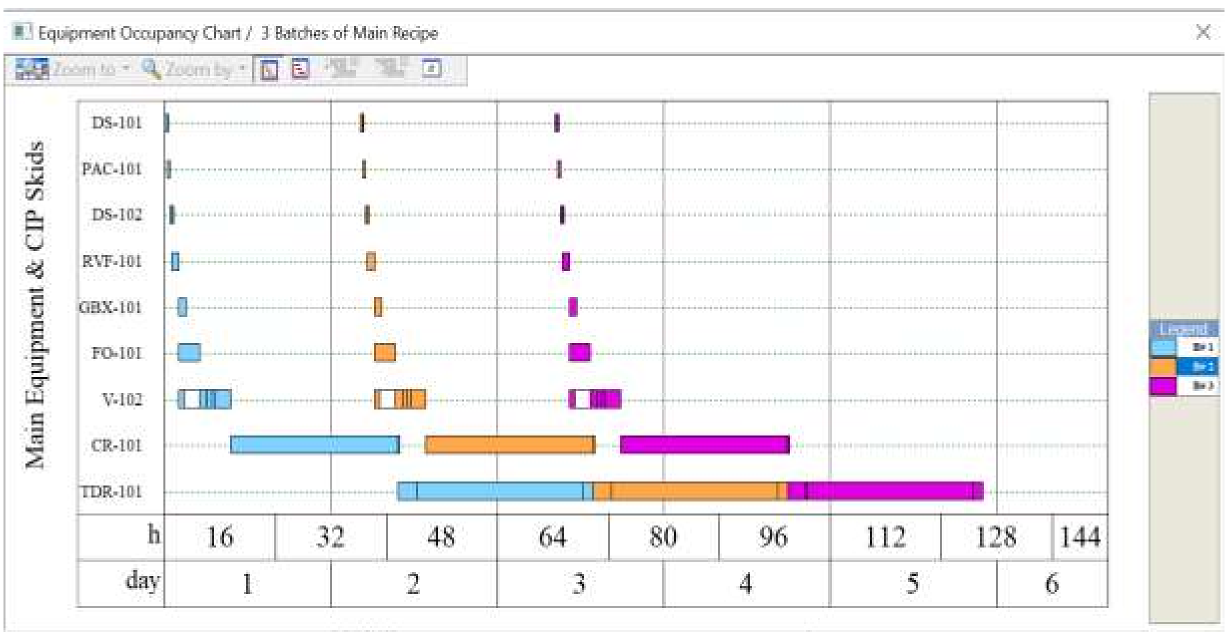

Figure 4.2-2: Equipment Occupancy Chart (EOC) for 3 batches.

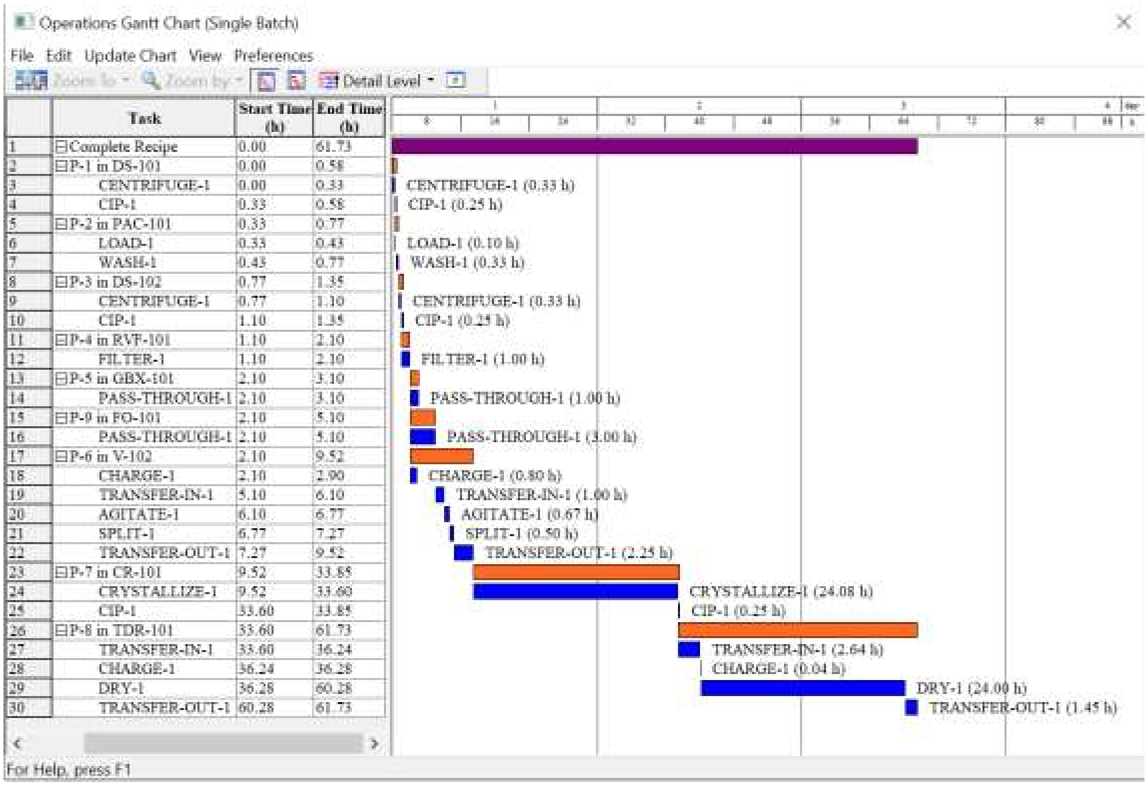

Figure 4.2-3: Operations Gantt Chart (single batch).

Figure 4.2-3 shows the Operations Gantt Chart for the process. This chart provides an overview of the full schedule for a single batch as a Gantt chart. The start time and end time of every task involved in this process is portrayed in the Gantt Chart, as well as the order of procedure in every equipment.

4.3 Economic Evaluation

In SuperPro Designer®, an Economic Evaluation Report (EER) can be generated by clicking on the Reports tab. For this study, the project lifetime was estimated for 15 years. Besides that, the construction period is 30 months, the startup period is 4 months and the inflation rate is set to be 4%. These assumptions are referred from (X. Li & Mupondwa, 2021), which are also the default value given by the software. Other than that, the capital, equipment and raw materials costs were estimated from the international cost provided by the software. The currency used in this study is Malaysian Ringgit (MYR) with a conversion rate of 1 USD equivalent to 4.24 MYR. The executive summary generated by the software is presented in Table 4.3-1, whereas Table 4.3-2 shows the fixed capital estimate summary for the proposed downstream process and its breakdowns.

Table 4.3-1: Executive Summary.

Component	Value (Cost shown in MYR and USD)	
Total Capital Investment	26,461,000 MYR	(6,240,802 USD)
Capital Investment Charged to This Project	26,461,000 MYR	(6,240,802 USD)
Operating Cost	23,223,000 MYR/yr	(5,477,123 USD/yr)
Revenues	34,762,000 MYR/yr	(8,198,585 USD/yr)
Cost Basis Batch Rate	3,545.07 kg UPRF	
Cost Basis Annual Rate	992,620 kg UPRF/yr	
Unit Production Cost	23.40 MYR/kg UPRF	(5.52 USD/kg UPRF)
Net Unit Production Cost	23.40 MYR/kg UPRF	(5.52 USD/kg UPRF)
Unit Production Revenue	35.02MYR/kg UPRF	(8.26 USD/kg UPRF)
Gross Margin	33.19%	
Return On Investment	34.66%	
Payback Time	2.88 years	
IRR (After Taxes)	22.42%	
NPV (at 7.0% Interest)	34,607,000 MYR	(8,162,028 USD)
UPRF = Total Flow of Stream 'Succinic Acid'		

Table 4.3-2: Fixed capital estimate summary for SA downstream process.

Fixed capital estimate summary	Cost (MYR)	Cost (USD)
A. Total Plant Direct Cost (TPDC)		
1. Equipment Purchase Cost	3,828,000	902,830
2. Installation	1,844,000	434,906
3. Process Piping	1,340,000	316,038
4. Instrumentation	1,531,000	361,085
5. Insulation	115,000	27,123
6. Electrical	383,000	90,330
7. Buildings	1,723,000	406,368
8. Yard Improvement	574,000	135,377
9. Auxiliary Facilities	1,531,000	361,085
TPDC	12,869,000	3,035,142
B. Total Unit Indirect Cost (TPIC)		
10. Engineering	3,217,000	758,726
11. Construction	4,504,000	1,062,264
TPIC	7,722,000	1,821,226
C. Total Plant Cost (TPC = TPDC + TPIC)		
TPC	20,591,000	4,856,368
D. Contractor's Fee & Contingency (CFC)		
12. Contractor's Fee	1,030,000	249,925
13. Contigency	2,059,000	485,613
CFC = 12+13	3,089,000	728,538
E. Direct Fixed Capital Cost (DFC = TPC+CFC)		
DFC	23,680,000	5,584,906

The fermentation broth used in this study was obtained from the supplier, where oil palm frond bagasse was hydrolyzed and employed as the carbon source for the fermentation process. The cost estimation of the fermentation broth was referred from (Bukhari et al., 2019) and it was noted that the processing cost of fermentation broth from the feedstocks was around USD 0.76/kg, which is approximately 3.3 MYR/kg. This estimated cost was employed in the simulation as the price of fermentation broth, due to the fact that fermentation process was not included in this study as it focuses only on the downstream part.

As seen in Table 4.3-1 above, the unit production cost is estimated to be 35.02 MYR/kg succinic acid according to the current market, as reported by (X. Li & Mupondwa, 2021). The economic analysis demonstrated a positive Net Present

Value (NPV) at 34,607,000 MYR (at 7% of interest). The gross margin is 33.19%, which means that 33.19% of the annual revenues are the gross profit of the process. Furthermore, the payback time is 2.88 years (approximately 2 years and 11 months). This indicates that it will take 2.88 years to recover the cost of the initial investment. The payback period for this process is considerably short, which proves that this project is economically feasible. In comparison, in a case study of bio-succinic acid commercialization conducted by (X. Li & Mupondwa, 2021), the payback time of the production plant is 10 years. Moreover, another noteworthy point is the process' Return on Investment (ROI) with a positive value of 34.66%. This indicates that the investment of the proposed project is an efficient investment and it could be an indicator of a viable process. Table 4.3-2 above shows the breakdown of the fixed capital estimate summary of succinic acid production. The values are obtained through the Economic Evaluation report generated by the software and it can be found in Section 3 of Appendix B. The formula used to calculate payback time and the Return on Investment (ROI) are written below.

$$Payback\ Time = \frac{Total\ Investment}{Net\ Profit} \quad \text{Eq. 4.3-1}$$

$$Return\ on\ Investment\ (ROI) = \frac{Net\ Profit}{Total\ Investment}\, x\ 100\% \quad \text{Eq. 4.3-2}$$

The operating costs in this process includes the costs of raw materials, labor-dependent, facility dependent, laboratory and utilities. Figure 4.3-1 shows a pie chart of the operating costs distribution for an annual succinic acid production.

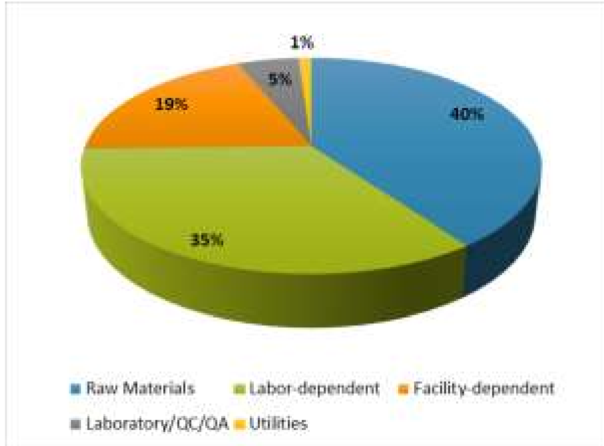

Figure 4.3-1: Operating costs distribution (per year).

From the information shown in the pie chart in Figure 4.3-1, it is clear that the costs of raw materials represent the largest portion of the total operating costs at 40 percent, which is mainly attributed to the cost of obtaining the fermentation broth. If the cost of the fermentation process decreased or lower-priced raw materials can be found, then these costs can be reduced. Labor-dependent costs contribute to the second highest consumption at 35 percent. Besides that, facility-dependent costs came third with 19 percent. These costs can be reduced by increasing equipment sharing although it might result in the decrease in annual throughput. Laboratory/QC/QA costs represent only 5 percent of the total operating costs. Lastly, utilities require lowest cost, at only 1 percent.

4.4 Sensitivity Analysis

A sensitivity analysis was carried out in order to provide more detailed insights on the impact of different variables upon the economic performance of the process. Two variables, which are the cost of fermentation broth obtained from the fermentation process and the selling price of SA crystals, are independently evaluated in this analysis. Both cost parameters are simulated with a fluctuation of ±25%. This is because the global economic environment is likely to fluctuate over the lifetime of a plant (Czinkóczky & Németh, 2020). Payback time, NPV and ROI were selected as the economic indicators in this study and were compared with the values obtained in the base case (default). Table 4.4-1 represents the results obtained from the sensitivity analysis.

	Fermentation Broth Purchasing Price			**Succinic Acid Selling Price**	
	Default	**-25%**	**25%**	**-25%**	**25%**
Payback time (yr)	3.32	2.75	4.19	9.2	2.02
ROI (%)	30.1	36.38	23.88	10.86	49.38
NPV (MYR)	26,118,000	37,577,000	16,805,000	-9,596,000	62,894,000

It can be observed in the results obtained that the lower cost of fermentation broth resulted in a shorter payback time as well as a higher ROI. This means that a higher profit can be gained if the broth is obtained at a cheaper price. On the contrary, if the fermentation broth is 25% more expensive than the base case, the plant will take a longer time to payback the initial investment. Besides that, the value of ROI% also decreased, which will consequently contribute to the reduce of profit. However, for both cases, the values of NPV are positive, which means that the project is still viable.

On the other hand, the selling price of succinic acid demonstrated a more significant impact on the economic indicators. For example, a reduce in the selling price at -25% resulted in 6.65 years of payback time. Although this could be seen as a considerably acceptable payback time for a plant with a lifetime of 15 years, the low selling price contributed to a negative NPV. This means that this project is expected to result in a net loss and this investment should not be undertaken. On the other hand, a higher selling price obviously resulted in a shorter payback time, higher ROI and a more positive NPV value. However, this comes with some disadvantages, such as some sales may be lost because customers are not willing to pay the higher price. Besides that, other competitors may take away the market by introducing a lower-priced product.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The production of bio-based succinic acid is continuously being studied due to its strengths and opportunities in the market, and thus more researches are conducted to improve the technology of the downstream process of succinic acid production. Process simulation software, specifically SuperPro Designer® is very useful in order to evaluate the process and identify the important factors for the process' economy feasibility. From the recipe scheduling of the process, the equipment with the longest duration to complete was found to be the tray dryer (TDR-101) which is the final equipment in this process. At the end of every batch, 3545.07 kg of 98% pure succinic acid crystals were recovered as final product with a recovery yield of 89%. Results from the economic evaluation showed that the payback time for this project is 2.88 years, whereas the unit production cost was estimated to be 23.40 MYR/kg. The overall findings demonstrated that this project is viable according to the economic evaluation that has been carried out.

5.2 Recommendation

SuperPro Designer® is a very useful software in simulating a process to study its economic feasibility. However, it is a known fact that this simulation model is less complex than the real case of a production plant. Following the economic uncertainty in the country, there is a need for further research on various risks and uncertainties. These includes funding, loads, foreign exchange rate and many more. In order to carry out these studies, a vast knowledge and resources on the risk mitigation are required.

It is also recommended as a future work to build a simulation model of a complete production plant, starting from the fermentation process in order to carry out comparison with other researches as most of the literatures available currently cover the economic analysis of a complete production plant.

Last but not least, more comprehensive technology assessment of forward osmosis technology should be done in the future with a more detailed simulation model.

REFERENCES

Anisi, F., Mathew Thomas, K., & Kramer, H. J. (2016). *Membrane-assisted crystallization: Membrane characterization, modelling and experiments A R T I C L E I N F O*. https://doi.org/10.1016/j.ces.2016.10.036

Bergman, E. (2016). *Evaluation of the software SuperPro Designer through simulation of a biohydrogen production process*.

Bio-Based Succinic Acid Market – Global Industry Trends and Forecast to 2027 | Data Bridge Market Research. (n.d.). Opgehaal 06 Mei 2021, van https://www.databridgemarketresearch.com/reports/global-bio-based-succinic-acid-market

Bukhari, N. A., Loh, S. K., Nasrin, A. B., Luthfi, A. A. I., Harun, S., Abdul, P. M., & Jahim, J. M. (2019). Compatibility of utilising nitrogen-rich oil palm trunk sap for succinic acid fermentation by Actinobacillus succinogenes 130Z. *Bioresource Technology*, *293*(June). https://doi.org/10.1016/j.biortech.2019.122085

Cheng, K. K., Zhao, X. B., Zeng, J., Wu, R. C., Xu, Y. Z., Liu, D. H., & Zhang, J. A. (2012). Downstream processing of biotechnological produced succinic acid. In *Applied Microbiology and Biotechnology* (Vol 95, Number 4, bll 841–850). Springer. https://doi.org/10.1007/s00253-012-4214-x

Choi, S., Song, C. W., Shin, J. H., & Lee, S. Y. (2015). Biorefineries for the production of top building block chemicals and their derivatives. In *Metabolic Engineering* (Vol 28, bll 223–239). Academic Press Inc. https://doi.org/10.1016/j.ymben.2014.12.007

Clews, R. J. (2016). The Petrochemicals Industry. In *Project Finance for the International Petroleum Industry* (bll 187–203). Elsevier. https://doi.org/10.1016/b978-0-12-800158-5.00011-6

Crystallization. (n.d.). Opgehaal 24 Junie 2021, van http://www.reciprocalnet.org/edumodules/crystallization/

Czinkóczky, R., & Németh, Á. (2020). Techno-economic assessment of Bacillus fermentation to produce surfactin and lichenysin. *Biochemical Engineering Journal*, *163*(July), 107719. https://doi.org/10.1016/j.bej.2020.107719

Dienst, S., & Onderzoek, L. (2015). | *Strategic thinking in sustainable energy From the Sugar Platform to biofuels and biochemicals Final report for the European Commission Directorate-General Energy Consorzio per la Ricerca e la Dimostrazione sulle Energie Rinnovabili (RE-CORD)*.

Drioli, E., Di Profio, G., & Curcio, E. (2012). Progress in membrane crystallization. In *Current Opinion in Chemical Engineering* (Vol 1, Number 2, bll 178–182).

Elsevier Ltd. https://doi.org/10.1016/j.coche.2012.03.005

Ferone, M., Raganati, F., Olivieri, G., & Marzocchella, A. (n.d.). *Bioreactors for succinic acid production processes HyperMicroMacro: Multi-scale hyperspectral imaging for enhanced understanding and control of food microbiology View project Waste2Fuels View project*. https://doi.org/10.1080/07388551.2019.1592105

Garcia-Aguirre, J., Alvarado-Morales, M., Fotidis, I. A., & Angelidaki, I. (2020). Up-concentration of succinic acid, lactic acid, and ethanol fermentations broths by forward osmosis. *Biochemical Engineering Journal*, *155*, 107482. https://doi.org/10.1016/j.bej.2019.107482

García-Fernández, L., Khayet, M., & García-Payo, M. C. (2015). Membranes used in membrane distillation: Preparation and characterization. In *Pervaporation, Vapour Permeation and Membrane Distillation: Principles and Applications* (bll 318–359). Elsevier Ltd. https://doi.org/10.1016/B978-1-78242-246-4.00011-8

Gupta, S., & Pathak, B. (2019). Mycoremediation of polycyclic aromatic hydrocarbons. In *Abatement of Environmental Pollutants: Trends and Strategies* (bll 127–149). Elsevier. https://doi.org/10.1016/B978-0-12-818095-2.00006-0

Harun, N., Othman, N. A., Zaki, N. A., Mat Rasul, N. A., Samah, R. A., & Hashim, H. (2019). Simulation of Anaerobic Digestion for Biogas Production from Food Waste Using SuperPro Designer. *Materials Today: Proceedings*, *19*, 1315–1320. https://doi.org/10.1016/j.matpr.2019.11.143

Herva, M., Franco, A., Carrasco, E. F., & Roca, E. (2011). Review of corporate environmental indicators. *Journal of Cleaner Production*, *19*(15), 1687–1699. https://doi.org/10.1016/j.jclepro.2011.05.019

Huh, Y. S., Jun, Y. S., Hong, Y. K., Song, H., Lee, S. Y., & Hong, W. H. (2006). Effective purification of succinic acid from fermentation broth produced by Mannheimia succiniciproducens. *Process Biochemistry*, *41*(6), 1461–1465. https://doi.org/10.1016/j.procbio.2006.01.020

IHS CHEMICAL Chemical Industry Capital Costs: A Global Spending Outlook Special Report Prospectus IHS Chemical Prospectus IHS CHEMICAL 2. (2015).

Intelligen, Inc. (n.d.). Opgehaal 01 April 2021, van https://www.intelligen.com/products/superpro-designer/superpro-designer-brief-overview/

Jusoh, N., Sulaiman, R. N. R., Othman, N., Noah, N. F. M., Rosly, M. B., & Rahman, H. A. (2020). Development of vegetable oil-based emulsion liquid membrane for downstream processing of bio-succinic acid. *Food and Bioproducts Processing*, *119*, 161–169. https://doi.org/10.1016/j.fbp.2019.11.003

Khalid, S. A. (2015). Investopedia. In *FIIB Business Review: Vol Vol.4* (Iss.4, bll 43–48). https://www.proquest.com/openview/71ca67b08296564cebbe09ad77d29f92/1?pq-origsite=gscholar&cbl=2046370

Law, J. Y., & Mohammad, A. W. (2018). Osmotic concentration of succinic acid by forward osmosis: Influence of feed solution pH and evaluation of seawater as draw solution. *Chinese Journal of Chemical Engineering*, *26*(5), 976–983. https://doi.org/10.1016/j.cjche.2017.10.003

Law, J. Y., Mohammad, A. W., Tee, Z. K., Zaman, N. K., Jahim, J. M., Santanaraj, J., & Sajab, M. S. (2019). Recovery of succinic acid from fermentation broth by forward osmosis-assisted crystallization process. *Journal of Membrane Science*, *583*, 139–151. https://doi.org/10.1016/j.memsci.2019.04.036

Li, Q., Wang, D., Wu, Y., Li, W., Zhang, Y., Xing, J., & Su, Z. (2010). One step recovery of succinic acid from fermentation broths by crystallization. *Separation and Purification Technology*, *72*(3), 294–300. https://doi.org/10.1016/j.seppur.2010.02.021

Li, X., & Mupondwa, E. (2021). Empirical analysis of large-scale bio-succinic acid commercialization from a technoeconomic and innovation value chain perspective: BioAmber biorefinery case study in Canada. *Renewable and Sustainable Energy Reviews*, *137*(September 2020), 110587. https://doi.org/10.1016/j.rser.2020.110587

López-Garzón, C. S., & Straathof, A. J. J. (2014). Recovery of carboxylic acids produced by fermentation. *Biotechnology Advances*, *32*(5), 873–904. https://doi.org/10.1016/J.BIOTECHADV.2014.04.002

Marinho, G. S., Alvarado-Morales, M., & Angelidaki, I. (2016). Valorization of macroalga Saccharina latissima as novel feedstock for fermentation-based succinic acid production in a biorefinery approach and economic aspects. *Algal Research*, *16*, 102–109. https://doi.org/10.1016/j.algal.2016.02.023

McKinlay, J. B., Vieille, C., & Zeikus, J. G. (2007). Prospects for a bio-based succinate industry. In *Applied Microbiology and Biotechnology* (Vol 76, Number 4, bll 727–740). Springer. https://doi.org/10.1007/s00253-007-1057-y

Nicoll, P. G. (2013). *FORWARD OSMOSIS-A BRIEF INTRODUCTION*.

Nieto, L., Rivera, C., Gelves, G., Nieto, L., Rivera, C., & Gelves, G. (2020). Economic Assessment of Itaconic Acid Production from Aspergillus Terreus using Superpro Designer. *JPhCS*, *1655*(1), 012100. https://doi.org/10.1088/1742-6596/1655/1/012100

Omwene, P. I., Yagcioglu, M., Ocal Sarihan, Z. B., Karagunduz, A., & Keskinler, B. (2020). Recovery of succinic acid from whey fermentation broth by reactive extraction coupled with multistage processes. *Journal of Environmental Chemical Engineering*, *8*(5), 104216.

https://doi.org/10.1016/j.jece.2020.104216

Operating Cost Definition. (n.d.). Opgehaal 22 Mei 2021, van https://www.investopedia.com/terms/o/operating-cost.asp

Pateraki, C., Patsalou, M., Vlysidis, A., Kopsahelis, N., Webb, C., Koutinas, A. A., & Koutinas, M. (2016). Actinobacillus succinogenes: Advances on succinic acid production and prospects for development of integrated biorefineries. In *Biochemical Engineering Journal* (Vol 112, bll 285–303). Elsevier B.V. https://doi.org/10.1016/j.bej.2016.04.005

Phanthumchinda, N., Thitiprasert, S., Tanasupawat, S., Assabumrungrat, S., & Thongchul, N. (2018). Process and cost modeling of lactic acid recovery from fermentation broths by membrane-based process. *Process Biochemistry*, *68*, 205–213. https://doi.org/10.1016/j.procbio.2018.02.013

Pinazo, J. M., Domine, M. E., Parvulescu, V., & Petru, F. (2015). Sustainability metrics for succinic acid production: A comparison between biomass-based and petrochemical routes. *Catalysis Today*, *239*, 17–24. https://doi.org/10.1016/j.cattod.2014.05.035

Powder activated carbon (PAC) | Desotec. (n.d.). Opgehaal 22 Mei 2021, van https://www.desotec.com/en/carbonology/carbonology-academy/powder-activated-carbon-pac

Rudner, M. S., Jeremic, S., Petterson, K. A., Kent IV, D. R., Brown, K. A., Drake, M. D., Goddard, W. A., & Roberts, J. D. (2005). Intramolecular hydrogen bonding in disubstituted ethanes. A comparison of NH···O - and OH···O - hydrogen bonding through conformational analysis of 4-Amino-4-oxobutanoate (succinamate) and monohydrogen 1,4-butanoate (monohydrogen succinate) anions. *Journal of Physical Chemistry A*, *109*(40), 9076–9082. https://doi.org/10.1021/jp052925c

Ruprakobkit, T., Ruprakobkit, L., & Ratanatamskul, C. (2019). Sensitivity analysis techniques for the optimal system design of forward osmosis in organic acid recovery. *Computers and Chemical Engineering*, *123*, 34–48. https://doi.org/10.1016/j.compchemeng.2018.12.024

Sharma, S., Jyoti Sarma, S., Kaur Brar, S., & York, N. (2020). BIO-SUCCINIC ACID: AN ENVIRONMENT-FRIENDLY PLATFORM CHEMICAL. *International Journal of Environment and Health Sciences (IJEHS)*, *2020*(2), 69–80. https://doi.org/10.47062/1190.0202.01

Song, H., & Lee, S. Y. (2006). Production of succinic acid by bacterial fermentation. *Enzyme and Microbial Technology*, *39*, 352–361. https://doi.org/10.1016/j.enzmictec.2005.11.043

Sosa, P. A., Roca, C., & Velizarov, S. (2016). Membrane assisted recovery and purification of bio-based succinic acid for improved process sustainability. *Journal of Membrane Science*, *501*, 236–247. https://doi.org/10.1016/j.memsci.2015.12.018

Succinic Acid - The Chemical Company. (n.d.). Opgehaal 16 Mei 2021, van https://thechemco.com/chemical/succinic-acid/

Succinic acid | chemical compound | Britannica. (n.d.). Opgehaal 11 Mei 2021, van https://www.britannica.com/science/succinic-acid

Succinic Acid Market Size, Share & Trends | 2020 - 2025. (n.d.). Opgehaal 06 Mei 2021, van https://www.marketdataforecast.com/market-reports/succinic-acid-market

Sun, Y., Zhang, X., Zheng, Y., Yan, L., & Xiu, Z. (2019). Sugaring-out extraction combining crystallization for recovery of succinic acid. *Separation and Purification Technology*, *209*, 972–983. https://doi.org/10.1016/j.seppur.2018.09.049

Sze, C., Lin, K., Du, C., Blaga, A. C., Asachi, G., Webb, C., Ki, S., Lin, C., Camarut, M., Stevens, C. V, & Soetaert, W. (2014). *Novel resin-based vacuum distillation-crystallisation method for recovery of succinic acid crystals from fermentation broths metabolic engineering View project Value-added products from biomass View project Novel resin-based vacuum distillation-crystallisation method for recovery of succinic acid crystals from fermentation broths*. https://doi.org/10.1039/B913021G

Takht, M., & Saeed Sahebdelfar, R. •. (n.d.). *Carbon dioxide capture and utilization in petrochemical industry: potentials and challenges*. https://doi.org/10.1007/s13203-014-0050-5

Thuy, N. T. H., & Boontawan, A. (2017). Production of very-high purity succinic acid from fermentation broth using microfiltration and nanofiltration-assisted crystallization. *Journal of Membrane Science*, *524*, 470–481. https://doi.org/10.1016/j.memsci.2016.11.073

Thuy, N. T. H., Kongkaew, A., Flood, A., & Boontawan, A. (2017). Fermentation and crystallization of succinic acid from Actinobacillus succinogenes ATCC55618 using fresh cassava root as the main substrate. *Bioresource Technology*, *233*, 342–352. https://doi.org/10.1016/j.biortech.2017.02.114

Willke, T., & Vorlop, K. D. (2004). Industrial bioconversion of renewable resources as an alternative to conventional chemistry. In *Applied Microbiology and Biotechnology* (Vol 66, Number 2, bll 131–142). Springer. https://doi.org/10.1007/s00253-004-1733-0

APPENDICES

A- Calculation of percentage of succinic acid recovery yield

$$Yield\ (\%) = \left(\frac{W_{SA}}{W_o}\right) x\ 100\%$$

$$Yield(\%) = \left(\frac{3545.07\ \frac{kg\ SA}{batch}}{4000\ \frac{kg\ SA}{batch}}\right) x\ 100\% = 89\%$$

B- Economic Evaluation Report generated by SuperPro Designer®

Economic Evaluation Report

for Rini Hazwani_FYP2_Simulation

1. EXECUTIVE SUMMARY (2021 prices)

Total Capital Investment	26,461,000 MYR
Capital Investment Charged to This Project	26,461,000 MYR
Operating Cost	23,223,000 MYR/yr
Revenues	34,762,000 MYR/yr
Cost Basis Batch Rate	3,545.07 kg UPRF
Cost Basis Annual Rate	992,620 kg UPRF/yr
Unit Production Cost	23.40 MYR/kg UPRF
Net Unit Production Cost	23.40 MYR/kg UPRF
Unit Production Revenue	35.02 MYR/kg UPRF
Gross Margin	33.19 %
Return On Investment	34.66 %
Payback Time	2.88 years
IRR (After Taxes)	22.42 %
NPV (at 7.0% Interest)	34,607,000 MYR

UPRF = Total Flow of Stream 'Succinic Acid'

2. MAJOR EQUIPMENT SPECIFICATION AND FOB COST (2021 prices)

Quantity/ Standby/ Staggered	Name	Description	Unit Cost (MYR)	Cost (MYR)
1 / 0 / 0	PAC-101	GAC Column	8,000	8,000
		Column Volume = 56.16 L		
9 / 0 / 0	DS-102	Disk-Stack Centrifuge	137,000	1,233,000
		Throughput = 2500.02 L/h		
1 / 0 / 0	RVF-101	Rotary Vacuum Filter	35,000	35,000
		Filter Area = 30.54 m2		
1 / 0 / 0	V-102	Blending Tank	65,000	65,000
		Vessel Volume = 8546.29 L		
1 / 0 / 0	CR-101	Crystallizer	177,000	177,000
		Vessel Volume = 8061.51 L		
10 / 0 / 0	DS-101	Disk-Stack Centrifuge	138,000	1,380,000
		Throughput = 2551.23 L/h		
1 / 0 / 0	FO-101	Generic Box	33,000	33,000
		Rated Throughput = 2860.37 kg/h		
4 / 0 / 0	TDR-101	Tray Dryer	33,000	132,000
		Tray Area = 67.36 m2		
		Unlisted Equipment		766,000
			TOTAL	3,828,000

3. FIXED CAPITAL ESTIMATE SUMMARY (2021 prices in MYR)

3A. Total Plant Direct Cost (TPDC) (physical cost)	
1. Equipment Purchase Cost	3,828,000
2. Installation	1,844,000
3. Process Piping	1,340,000
4. Instrumentation	1,531,000
5. Insulation	115,000
6. Electrical	383,000
7. Buildings	1,723,000
8. Yard Improvement	574,000
9. Auxiliary Facilities	1,531,000
TPDC	12,869,000

3B. Total Plant Indirect Cost (TPIC)	
10. Engineering	3,217,000
11. Construction	4,504,000
TPIC	7,722,000

3C. Total Plant Cost (TPC = TPDC+TPIC)	
TPC	20,591,000

3D. Contractor's Fee & Contingency (CFC)	
12. Contractor's Fee	1,030,000
13. Contingency	2,059,000
CFC = 12+13	3,089,000

3E. Direct Fixed Capital Cost (DFC = TPC+CFC)	
DFC	23,680,000

4. LABOR COST - PROCESS SUMMARY

Labor Type	Unit Cost (MYR/h)	Annual Amount (h)	Annual Cost (MYR)	%
Operator	291.87	27,449	8,011,530	100.00
TOTAL		27,449	8,011,530	100.00

5. MATERIALS COST - PROCESS SUMMARY

Bulk Material	Unit Cost (MYR)	Annual Amount		Annual Cost (MYR)	%
Air	0.00	28,000	kg	0	0.00
Fermentation Br	3.30	2,800,000	kg	9,240,000	99.26
H_2SO_4 (98% w/w)	0.29	28,000	kg	8,127	0.09
NaCl (5M)	2.48	9,632	kg	23,839	0.26
Water	0.00	8,709,130	kg	36,840	0.40
TOTAL				9,308,806	100.00

NOTE: Bulk material consumption amount includes material used as:

- Raw Material
- Cleaning Agent
- Heat Transfer Agent (if utilities are included in the operating cost)

6. VARIOUS CONSUMABLES COST (2021 prices) - PROCESS SUMMARY

Consumable	Units Cost (MYR)	Annual Amount		Annual Cost (MYR)	%
Dft GAC Packing (L)	16.92	0	kg	1	100.00
TOTAL				1	100.00

7. WASTE TREATMENT/DISPOSAL COST (2021 prices) - PROCESS SUMMARY

THE TOTAL WASTE TREATMENT/DISPOSAL COST IS ZERO.

8. UTILITIES COST (2021 prices) - PROCESS SUMMARY

Utility	Unit Cost (MYR)	Annual Amount	Ref. Units	Annual Cost (MYR)	%
Std Power	0.42	168,459	kW-h	71,258	28.58
Steam	50.76	736	MT	37,358	14.99
Steam (High P)	84.60	1,219	MT	103,100	41.36
Chilled Water	1.69	5,154	MT	8,721	3.50
NaCl Brine	1.06	27,293	MT	28,863	11.58
TOTAL				249,300	100.00

9. ANNUAL OPERATING COST (2021 prices) - PROCESS SUMMARY

Cost Item	MYR	%
Raw Materials	9,309,000	40.08
Labor-Dependent	8,012,000	34.50
Facility-Dependent	4,452,000	19.17
Laboratory/QC/QA	1,202,000	5.17
Consumables	0	0.00
Waste Treatment/Disposal	0	0.00
Utilities	249,000	1.07
Transportation	0	0.00
Miscellaneous	0	0.00
Advertising/Selling	0	0.00
Running Royalties	0	0.00
Failed Product Disposal	0	0.00
TOTAL	23,223,000	100.00

10. PROFITABILITY ANALYSIS (2021 prices)

A.	Direct Fixed Capital	23,680,000 MYR
B.	Working Capital	1,598,000 MYR
C.	Startup Cost	1,184,000 MYR
D.	Up-Front R&D	0 MYR
E.	Up-Front Royalties	0 MYR
F.	Total Investment (A+B+C+D+E)	26,461,000 MYR
G.	Investment Charged to This Project	26,461,000 MYR

H.	**Revenue/Savings Rates**	
	Succinic Acid (Main Revenue)	992,620 kg /yr

I.	**Revenue/Savings Price**	
	Succinic Acid (Main Revenue)	35.02 MYR/kg

J.	**Revenues/Savings**	
	Succinic Acid (Main Revenue)	34,761,537 MYR/yr
1	Total Revenues	34,761,537 MYR/yr
2	Total Savings	0 MYR/yr

K.	**Annual Operating Cost (AOC)**	
1	Actual AOC	23,223,000 MYR/yr
2	Net AOC (K1-J2)	23,223,000 MYR/yr

L.	**Unit Production Cost /Revenue**	
	Unit Production Cost	23.40 MYR/kg UPRF
	Net Unit Production Cost	23.40 MYR/kg UPRF
	Unit Production Revenue	35.02 MYR/kg UPRF

M.	Gross Profit (J-K)	11,538,000 MYR/yr
N.	Taxes (40%)	4,615,000 MYR/yr
O.	Net Profit (M-N + Depreciation)	9,173,000 MYR/yr

Gross Margin	33.19 %
Return On Investment	34.66 %
Payback Time	2.88 years

UPRF = Total Flow of Stream 'Succinic Acid'