Food Waste Digestate-Based Biorefinery Approach for Rhamnolipids Production: A Techno-Economic Analysis

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Abstract: The present work evaluates the techno-economic feasibility of a rhamnolipids production process that utilizes digestate from anaerobic digestion (AD) of food waste. Technical feasibility, profitability and extent of investment risks between fermenter scale and its operating strategy for rhamnolipids production was investigated in the present study. Three scenarios were generated and compared: production using a single large fermenter (Scenario I), using two small fermenters operated alternately (Scenario II) or simultaneously (Scenario III). It was found that all the scenarios were economically feasible, and Scenario III was the most profitable since it allowed the most optimum fermenter operation with utilization of multiple small-scale equipment to reduce the downtime of each equipment and increase the production capacity and overall productivity. It had the highest net present value, internal rate of return and shortest payback time at a discount rate of 7%. Finally, a sensitivity analysis was conducted to indicate how the variation in factors such as feedstock (digestate) cost, rhamnolipids selling price, extractant recyclability and process capacity influenced the process economics. The work provides important insights on techno-economic performance of a food waste digestate valorization process which would be useful to guide its sustainable scale-up.

Keywords: rhamnolipids; food waste; anaerobic digestate; techno-economic assessment; sensitivity analysis

1. Introduction

Food waste management is one of the most challenging environmental problems in recent times. This can be mainly attributed to the significant volumes of food waste generated globally and amounting to 1.3 billion tons [1,2]. Contrary to the conventional disposal method of landfilling, anaerobic digestion (AD) has gained considerable attention as a highly efficient food waste treatment method and converts it to bioenergy in the waste-to-energy approach [3]. However, while producing a clean and valuable resource, bioenergy, from food waste, AD leaves behind huge quantities of digestate at the end of the process [4]. Digestate is composed of a suspended solid fraction and a liquid fraction which contains soluble nutrients. It has an organic matter content of 68–72% which makes it a nutrient rich resource. It is estimated that 90–95% of feed added to the digester ends up in the digestate. Thus, with the increasing global prevalence of AD, increasing quantities of digestate are being generated which could therefore lead to the imminent risk of digestate becoming a ‘new waste’ in the near future [5]. For example, 80 million tons of digestate were produced in the EU from 117 AD plants processing organic material including food...
waste, farm waste, manure, etc. Therefore, the sustainability of AD plants depends on proper management of the digestate through creation of new value chains for this nutrient resource and providing new economic opportunities for AD [6,7].

In this context, we have recently developed a patented method for the bioconversion of digestate from food waste AD into rhamnolipids via fed-batch fermentation [8]. Rhamnolipids are a type of microbially produced glycolipid biosurfactants and consist of one (mono-rhamnolipid) or two rhamnose-units (di-rhamnolipid) as the glycon portion and one to three β-hydroxyfatty acid units as the aglycon portion. Examples of rhamnolipids structures are shown in Figure S1 (Supplementary Materials) [9]. Rhamnolipids possess excellent emulsification, wetting and foaming properties along with antimicrobial, anti-adhesive and biofilm disrupting activity, which makes them the most popular biosurfactant in the global market [10]. However, their processing from expensive feedstock thereby resulting in their high cost has restricted their market penetration. To this, the attractive features of our process such as the use of a low-cost feedstock (digestate) and high efficiency and productivity (10.25 g/L rhamnolipids produced within 43 h) debottleneck the challenges in rhamnolipids bioproduction. In our process, the rhamnolipids are produced as a dried powdered product without any extensive purification steps which makes them highly suitable for applications such as soil bioremediation, cleaners, detergents, microbial enhanced recovery, etc. The steps involved in this bioproduction are based on the process at laboratory scale (Figure 1).

![Schematic of steps in the conversion of food waste digestate to rhamnolipids.](image)

Waste-based sourcing of high-value products satisfies their renewability. However, a comprehensive evaluation of process economics of biotechnological processes in early design stage is imperative to identify the key process factors that can guide technological improvements and allow a sustainable scale-up. Such an analysis could facilitate improvement in process conversion yields and a consequent decrease in modeled production costs which is beneficial to reduce the investment risks prior to process commercialization [11,12]. In the present study, a techno-economic evaluation of the conversion of food waste digestate to rhamnolipids was performed. Technical feasibility, profitability and extent of
investment risks between fermenter scale and its operation strategy for rhamnolipids production was investigated in a plant. Three scenarios were generated and compared: production using a single large fermenter (Scenario I), using two small fermenters operated alternately (Scenario II) or simultaneously (Scenario III). Mass and utility balance calculations were performed and compared for each scenario to identify the most optimum one with the highest production capacity and overall productivity. Furthermore, a sensitivity analysis was conducted to evaluate the effect of crucial parameters on the minimum selling price of rhamnolipids. To the best of our knowledge, this is the first study that focusses on techno-economic assessment of rhamnolipids production using digestate from food waste AD.

2. Materials and Methods

2.1. Simulation Description

A plant was simulated to produce rhamnolipids from food waste digestate which was obtained from the Environmental Protection Department (EPD) facility, Hong Kong. Since the digestate (waste) reduction is supported by the government in Hong Kong, the relevant cost of logistics i.e., collection and transportation was not taken into consideration in this simulation [13]. The simulation of mass and energy balances, profitability, and sensitivity analysis were performed with Microsoft® Office Excel 2016. In addition, SuperPro Designer 8.5® was used to estimate the processing time of each production step. The annual production capacities in different scenarios were determined based on the available working volume of fermenters. Thus, the basis used in this assessment is utilization of 60% of the maximum fermenter volumes to produce rhamnolipids from digestate. The plant is in Hong Kong or the Greater Bay Area (GBA) with a plant lifetime of 15 years (7884 operating hours per year), excluding the 3 years of construction and start-up phase. The working volume of fermenter is set at 60% of the maximum volume since a lot of foaming occurs in this fermentation process.

2.2. Process Description

2.2.1. Rhamnolipids Production Process

This study is based on the experimental results obtained from laboratory scale experiments [8]. The process flow diagram is depicted in Figure 2 while the process parameters are shown in Table 1. As can be seen in Figure 2, shake flasks containing nutrient broth as the cultivation medium were first inoculated by *Acinetobacter calcoaceticus* BU-03 [14]. The bacteria were cultivated using nutrient broth as a substrate under a temperature of 55 °C and a shaking speed of 150 rpm during 16 h of shake flask operation. This was followed by seed fermentation in a 0.35 m³ seed fermenter. Subsequently, the culture was transferred to a 3.5 m³ seed fermenter for first-stage fermentation using nutrient broth. Second stage fermentation was then performed with digestate in a 35 m³ seed fermenter. The above fermentation steps in the three seed fermenters were performed for 24 h each. Food waste digestate was used without any pretreatment (centrifugation, filtration etc.) and culture inoculation was 10% (v/v). Lastly, the production stage fermentation was performed in a 350 m³ fermenter for 43 h. The fermenters were sterilized together with the food waste digestate inside the fermenter by heating to a temperature of 121 °C and holding at 121 °C for 1 h. Then the fermenters were cooled to room temperature using cooling water before being operated aerobically under batch fermentation mode with a temperature of 55 °C and pH of 7.5. It was assumed that during these fermentation processes at 55 °C, no volume of broth was lost due to evaporation.
Figure 2. Process flow diagram for rhamnolipids fermentation using food waste digestate.

The yield of the process as determined through laboratory-scale experiment was 10 g rhamnolipids produced from 1 L of food waste digestate. Following the fermentation process, the downstream operations were carried out to extract rhamnolipids. The fermentation broth with an original pH of 7.5 was used for rhamnolipids extraction. For this, centrifugation and filtration of fermentation broth was performed to remove the biomass and solid impurities. Subsequently, extraction and purification of crude rhamnolipids from the cell-free supernatant was performed through hexane extraction in which a ratio of 1:3 (v/v) of n-hexane to supernatant was used. The extraction was performed three times to allow complete extraction of rhamnolipids into the organic layer. For the extraction process used in the present study, neither the pH was adjusted prior to hexane extraction nor the acid precipitation of rhamnolipids was performed. The method was the same as reported previously by Zhao and Wong (2009) and Wong et al. for the same rhamnolipid producer strain as the one used in this study and wherein no pH adjustment was used either [14,15]. The mixture of rhamnolipids foam and hexane was passed through the distillation process to remove hexane. It was assumed here that 99% of hexane used during extraction process can be recycled from the distillation process. Lastly, partially purified rhamnolipids were freeze-dried to obtain solid rhamnolipids with longer shelf-life. Liquid chromatography–mass spectrometry (LC-MS) was used for confirmation and characterization of rhamnolipids (results not shown here).

The method of extracting rhamnolipids using n-hexane used in the present study deviates from the previous literature reports by Müller et al. and El-Housseiny et al. who reported the use of n-hexane to determine the oil content in the fermentation media but not for rhamnolipids extraction from this oil-containing medium [16,17]. On the contrary, a recent report by Zhou et al. suggested that rhamnolipids could be extracted from the fermentation broth using n-hexane in the presence of oil due to the formation of reverse micelles [18]. Zhou et al. first performed acid precipitation of rhamnolipids produced in an oil-containing fermentation medium followed by its extraction with n-hexane. The group further showed the effect of pH in acid-precipitated rhamnolipids on extraction by n-hexane and suggested a lower pH of 4.5 for obtaining increased yields of rhamnolipids. This was reasoned due to the carboxyl groups of rhamnolipids being more protonated and exhibiting nonionic behavior at acidic pH to allow an easier dissolution into hexane. This is an interesting method to extract rhamnolipids which could be explored in future rhamnolipids research to replace the conventionally used solvents e.g., chloroform which is toxic. With no pH adjustment and/or acid precipitation of rhamnolipids, the method in the present study could successfully extract rhamnolipids from the digestate-based
fermentation broth using n-hexane. Future investigations could be based on the method by Zhou et al. to possibly improve the rhamnolipids extraction yields. However, the additional cost of oil needed for extraction would be an important factor to consider.

Table 1. General parameters for techno-economic evaluation.

| Items                                | Estimation Assumption                                                                 |
|--------------------------------------|---------------------------------------------------------------------------------------|
| Plant location                       | Hong Kong or other GBA core city                                                     |
| Plant capacity                       | Depends on processing time per batch of each scenario                                 |
| Annual production time               | 7884 operating hours per year                                                        |
| Feedstock                            | Food waste digestate from EPD, Hong Kong (without any pretreatment)                   |
| Main products                        | Rhamnolipids (50% purity)                                                            |
| Mass balance                         |                                                                                      |
| Fermentation yield                   | 10 g rhamnolipids L\(^{-1}\) food waste digestate                                      |
| Rhamnolipids recovery                | 100% by weight                                                                        |
| Rhamnolipids purity                  | Rhamnolipids product is sold at 50% purity by weight                                  |
| Processing time per batch *          |                                                                                      |
| Scenario I                           | 52.8 h                                                                                |
| Scenario II                          | 60.4 h #                                                                              |
| Scenario III                         | 50.0 h #                                                                              |
| Total capital investment (TCI)       |                                                                                      |
| Direct costs (DC)                    |                                                                                      |
| Total equipment cost (TEC)           | 1.00 × TEC                                                                            |
| Installation                         | 0.74 × TEC                                                                            |
| Instrumentation and control          | 0.43 × TEC                                                                            |
| Piping and insulation                | 0.40 × TEC                                                                            |
| Electrical system                    | 0.13 × TEC                                                                            |
| Buildings                            | 0.47 × TEC                                                                            |
| Service facilities                   | 0.85 × TEC                                                                            |
| Land acquisition                     | 0.06 × TEC                                                                            |
| Yard improvement                     | 0.15 × TEC                                                                            |
| Indirect costs (IC)                  |                                                                                      |
| Engineering and supervision          | 0.34 × TEC                                                                            |
| Construction and legal expenses      | 0.42 × TEC                                                                            |
| Total direct and indirect costs (TDIC)| DC + IC = 4.99 × TEC                                                                  |
| Contractor’s fee                     | 0.05 × TDIC = 0.18 × TEC                                                             |
| Contingency                          | 0.10 × TDIC = 0.36 × TEC                                                             |
| Fixed capital investment (FCI)       | DC + IC = 5.53 × TEC                                                                  |
| Working capital (WC)                 | 15% × TCI = 0.98 × TEC                                                                |
| Total capital investment (TCI)       | FCI + WC = 6.51 × TEC                                                                 |
| Rhamnolipids production cost (RLPC)  |                                                                                      |
| Raw material cost                    | USD 7.64 kg\(^{-1}\) rhamnolipids (from mass balance and known unit price)           |
| Utility                              | Electricity (USD 0.122 kW\(^{-1}\) h\(^{-1}\)), steam (USD 12.00 MT\(^{-1}\)), and cooling water (USD 0.03 m\(^{-3}\)) |
Table 1. Cont.

| Items                                | Estimation Assumption                                      |
|--------------------------------------|------------------------------------------------------------|
| Operating labor                      | According to Peters and Timmerhaus (2003) [19], Ulrich (1984) [20] |
| Direct supervisory and clerical labor| 15% of operating labor                                     |
| Maintenance and repairs              | 4% of fixed capital investment (FCI)                       |
| Operating supplies                   | 15% of maintenance and repairs                             |
| Laboratory charges                   | 15% of operating labor                                     |
| Patent and royalties                 | 3% of total product cost                                   |
| Depreciation                         | Straight-line depreciation over 15-year lifetime           |
| Local taxes and insurance            | 2% of fixed capital investment (FCI)                       |
| Plant overhead costs                 | 60% of labor, supervision, and maintenance                |
| Administrative costs                 | 15% of labor, supervision, and maintenance                |
| Research and Development Costs (R&D) | 3% of revenue                                              |
| Distribution and marketing costs     | 14% of total product cost                                  |
| Contingency                          | 3% of total product cost                                   |
| Logistic cost                        | Approved by Government                                     |
| Revenue                              |                                                            |
| Rhamnolipids (50% purity)            | USD 225 kg\(^{-1}\)                                        |

* The value shown here is the processing time per batch of equal rhamnolipid production quantity of the bottleneck process in each scenario. These provide the estimation of annual operating hours for each scenario (Table S1). * Halved using two fermenters. GBA: Greater Bay Area; EPD: Environmental Protection Department; MT: metric tons.

2.2.2. Scenarios Assessed in This Study

The techno-economic assessment was performed under three different scenarios. These scenarios were compared to show the effectiveness of minimizing the downtime of equipment on increasing the process profitability. Scenario I utilizes one large-scale fermenter e.g., one 350 m\(^3\) fermenter for production stage, as described in Section 2.2.1. Scenario II has a similar process as Scenario I, however, the main difference is that two smaller-scale production fermenters (2 × 175 m\(^3\)) are used in this scenario in an alternate mode as opposed to one large-scale production fermenter used in Scenario I. In addition, the sizes of all seed fermenters as mentioned in Scenario I are also halved in Scenario II. The following equipment is used in Scenario II.

- One each for the three seed fermenters with half size as in Scenario I i.e., 0.175, 1.75, and 17.5 m\(^3\)
- Two small-scale fermenters for production stage with half size as in Scenario I i.e., 175 m\(^3\) each.

The production stage (43 h) requires more time than the other two previous seed fermentation stages. Thus, the alternate use of two half-scale production stage fermenters in Scenario II would minimize the downtime of all seed fermenters i.e., once all seed fermentation processes are finished, the broth can immediately be transferred to the production stage without any waiting.

Scenario III utilizes two half-scale fermenters for each seed fermentation stage as well as the production stage. In scenario III, the following equipment is utilized.

- Two each for the three seed fermenters with half size as in Scenario I i.e., 0.175, 1.75, and 17.5 m\(^3\).
- Two small-scale fermenters for production stage with half size as in Scenario I i.e., 175 m\(^3\) each.

In this scenario, two fermentation processes can be performed simultaneously without the requirement of any downtime for all fermenters. This means that two batches of half-
scale rhamnolipids production can be operated simultaneously, as opposed to Scenario I which involves only one batch of large-scale rhamnolipids production operating at a time. Table S2 (Supplementary Materials) shows the total equipment costs and total capital investment for each scenario.

2.2.3. Estimation of Processing Time per Batch in Each Scenario

It is important to note that the processing time per batch in each scenario is different since each scenario has different scale of fermenters being used. Smaller scale fermenters should have lower processing time due to the shorter pumping, cleaning, and heating time. However, the utilization of multiple smaller scale fermenters will result in a higher capital investment. Processing time per batch is defined as the time required to produce one batch of the same amount of rhamnolipids. Since all fermenters have maximum allowable working volume of 60% of the total volume, the production capacity per batch can be determined by multiplying the rhamnolipids yield (10 g rhamnolipids from 1 L of food waste digestate) with the maximum allowable amount of food waste digestate per batch of production. Although all scenarios have the same amount of rhamnolipids produced per batch of fermentation, the annual production capacity is different due to the different processing time per batch. To put it simply, the shorter the processing time per batch, the higher the annual production capacity.

In order to estimate the processing time per batch of each scenario, several simulations were performed in SuperPro Designer 8.5®. Assumptions were made during these simulations which included heating rate of small-scale fermenter of 1 °C/min, heating rate of large-scale fermenter of 0.75 °C/min, holding time of sterilization at 121 °C = 1 h, and pump rate of 100 m³/h. Using these parameters and several additional parameters built in SuperPro Designer 8.5®, the processing time per batch for each scenario was determined, which can subsequently be used for estimating the annual production capacity. Results of estimation of processing time per batch of each scenario are provided in Table 1. From Table 1, it can be seen that Scenario III has the least processing time per batch, i.e., 50 h. Further details on the annual operating hours for each unit operation for all the scenarios are provided in Table S1 (Supplementary Materials).

2.3. Economic Evaluation

The economic evaluation was conducted by calculating three important values which are capital investment, production costs, and revenue generation. Following this, profitability and sensitivity analyses were performed.

2.3.1. Total Capital Investment Estimation

The total capital investment constitutes direct cost, indirect costs, and working capital for start-up costs. The direct cost includes total equipment costs with installation, piping, instrumentation, electrical system, buildings, and other plant construction related costs, while the indirect costs include costs associated with engineering and supervision, legal and construction expenses. The calculation factors were estimated based on the method of percentage of total equipment costs for grass-root solid-fluid processing plant, as presented in Peters and Timmerhaus [19]. The equipment costs were mainly estimated by using the unit price data from a technical report by Humbird et al. [21]. For the equipment not listed in the report, unit price was determined by referring to the data from techno-economic analysis reported by Kwan et al. and Wang et al. [11,12]. The unit price of each equipment was estimated by multiplying the known unit price from the reference by Chemical Engineering Plant Cost Index (CEPCI) factor and the scaling factor [11]. The CEPCI factor in 2018 was taken as the current CEPCI in this work, which was 603.1. The equipment unit prices and scaling factors were obtained from Humbird et al. [21]. The only exceptions were the unit prices and scaling factors of extractor and distillation which
were obtained from Kwan et al. [11], and the freeze-dryer which were obtained from Wang et al. [12]. The equipment unit prices were calculated using the Equation:

\[ \frac{P}{P_{t0}} = CEPCI_{2018} \times \frac{P_{t0}}{X_{t0}} \times \left( \frac{X}{X_{t0}} \right)^n \]  

where \( P \) = equipment unit price used in this study, \( CEPCI_{2018} \) is 603.1, \( CEPCI_{t0} \) is the CEPCI at time when the \( P_{t0} \) was estimated, \( P_{t0} \) is the unit price in the reference, \( X \) is the equipment capacity used in this study, \( X_{t0} \) is the equipment capacity in the reference, and \( n \) is the scaling factor according to the reference. The equipment cost for each operation is shown in Table S2 (Supplementary Materials).

Installation costs were equipment-specific and were estimated by multiplying each equipment cost with its unique installation factors which are available in the literature [11,21]. Although it is expected to obtain rent-free land from support of the Hong Kong government, the location cost was estimated to be 6% for this techno-economic assessment [13,19]. The working capital, which is estimated to be 15% of the total capital investment, is necessary to cover the expenses during the plant start-up phase. Lastly, it was assumed that there was no salvage value at the end of plant lifetime. The summary of total capital investment estimation method is listed in Table 1.

### 2.3.2. Rhamnolipids Production Cost Estimation

The rhamnolipid production cost was estimated by adding the feedstock costs, utility and labor costs, and general expenses. To calculate the raw material costs, it is necessary to determine the unit price of each feedstock which were referred from the available market price online [4,22–26]. With the known unit price of feedstock and known mass balance from the laboratory-scale experiment, the total cost of feedstock was estimated to be USD 7.64 per kg of rhamnolipids. The annual feedstock cost could then be calculated by multiplying USD 7.64 by annual rhamnolipids production capacity.

Utilities (electricity, steam, and cooling water) were calculated by referring to the utility costs for Hong Kong as stated in the techno-economic assessment by Kwan et al. [11]. Utility cost related to each equipment was estimated by comparing the production capacity of each equipment used in this study with the one used in Kwan et al. and using the scaling factor of each equipment [11].

\[ U = U_{t0} \times \left( \frac{X}{X_{t0}} \right)^n \]  

where \( U \) is utility usage of each equipment in this study, \( U_{t0} \) is the utility usage in the reference, \( X \) is the equipment capacity in this study, \( X_{t0} \) is the equipment capacity in the reference, and \( n \) is the scaling factor from the reference.

One exception was the utility usage of freeze-drying, which was calculated based on the information that the electricity usage per kilogram of product was 17.84 kWh [27]. The other exception was the calculation of electricity usage during sterilization, which was calculated using the Equation:

\[ Q = m \times c \times \Delta T \]  

where \( Q \) = heat required, \( m \) = mass of the material, \( c \) = heat capacity of the material, and \( \Delta T \) = difference in temperature. Batch sterilization in place (SIP) is conducted inside the fermenter. Detailed utility usage for each unit operation is shown in Table S3 (Supplementary Materials). Unit costs of each utility aspect are listed in Table 1. By using the comparison analysis as well as the above equation, the annual utility costs were estimated.

The labor cost was estimated by using the method from Peters and Timmerhaus [19] and Ulrich [20]. Salary was estimated based on the average annual salary of chemical engineers in Hong Kong = HKD 285,000/year (USD 36,774/year) [28]. By assuming that 1 working year consists of 52 weeks of work and 40 h per week, the total working hours of each year is 2080 h/year. Then, the operator salary per hour can be calculated to be USD 36,774/2080 = USD 17.68/hour. Since the operating hours per batch of each equipment is
known, the annual operating hours of each equipment can be calculated by multiplying the operating hours per batch by number of batches per year (shown in Table S1). After obtaining the annual operating hours of each equipment, the operators’ annual working hours for that specific equipment can be approximated by using the data from Peters and Timmerhaus [19] and Ulrich [20]. By using the data from these references, the number of operators necessary per unit for each specific equipment can be estimated. Following this, the annual working hours can be calculated by multiplying the operating hours with the number of operators per unit of each equipment. Lastly, the labor cost can be obtained by multiplying operators’ annual working hours with the average salary per hour (USD 17.68/h/operator). A detailed estimation of labor cost is provided in Table S4 (Supplementary Materials). Table S5 provides a summary of all the associated costs for each operation in each scenario (Supplementary Materials).

Other associated general expenses such as supervision, maintenance and repairs, plant overhead costs, and contingency were estimated using the data from Peters and Timmerhaus [19]. Table 1 provides a summary of components estimation for the cost of rhamnolipids production in this study. It should be emphasized that the total equipment cost (TEC) directly impacts rhamnolipids production cost, i.e., the latter increases with a higher TEC.

2.3.3. Revenue

Revenue is generated from the sales of dried rhamnolipids (50% purity by weight). According to Natsurfact [29], the current market price of 50% pure rhamnolipids is USD 225 per kg.

2.3.4. Profitability Analysis

To determine profitability, it is necessary to firstly state some assumptions. The first three years will be focused on initialization, planning, and construction of the plant. The capital investment costs will be utilized in these first three years (Year 1–3). In the first year of production (Year 4), only 50% of the plant capacity will be utilized for rhamnolipids production. It is common for a biochemical plant to produce lesser quantity in the first year of production in order to reduce the risk of overproduction, place more focus on marketing the product, and familiarize and train the engineers and employees with the plant. Following the first year of production (Year 5 and later), the plant will operate at the full production capacity. The taxation of gross profit is set at 16.5% and the interest rate is set at 7%.

After the above assumptions were made, the profitability of each scenario was analyzed by determining the gross profit, net profit, minimum selling price, cumulative net present value (NPV), and the internal rate of return (IRR). Gross profit is defined as annual revenue minus the annual production costs. Net profit is calculated by subtracting 16.5% taxation from gross profit. Minimum selling price is determined when the net profit equals zero. Cumulative NPV is the difference between present value of cash inflows and cash outflows at the end of the plant lifetime.

\[
NPV \text{ (US$)} = \sum_{t=1}^{T} \frac{CF_t}{(1 + r)^t} - CF_0
\]  

where \(t\) is the current age of plant in years, \(T\) is the final plant lifetime in years, \(CF_t\) is the cash flow during period \(t\), \(CF_0\) represents initial investment, and \(r\) is the discount rate. IRR is the discount rate where the cumulative NPV becomes zero at the end of plant lifetime. IRR is frequently used to evaluate the attractiveness and potential of a project. As IRR increases, the project becomes more attractive to the investors.
2.3.5. Sensitivity Analysis

A sensitivity analysis was performed to assess the effect of different variables on the economic performance in each scenario. The variables assessed included the cost of food waste digestate, rhamnolipids selling price, annual rhamnolipids production capacity, hexane recyclability, and land cost.

3. Results and Discussion

3.1. Mass Balance

The mass balance is calculated using the information obtained from laboratory experimental results. The process flow diagram and mass balance of rhamnolipids yield and purification are presented in Figure 2 and Table 1, respectively. It was found that under optimized conditions, 10 g of rhamnolipids can be produced from 1 L of digestate [8]. Assuming that no volume is lost by evaporation during fermentation, no rhamnolipids are lost in the downstream processes and hexane can be 99% recycled in the extraction process, the results of mass balance are shown in Table 1. Acid, base, and antifoam are used in the process for pH and foam control. The basis of the calculation is 60% of the maximum volume of fermenter. In Scenario I, the fermenter in production stage has a maximum volume of 350 m$^3$. Hence, the basis of calculation in Scenario I is 210 m$^3$ of food waste digestate per batch. With the yield of 10 g rhamnolipids for every 1 L of food waste digestate, it can be calculated that 2100 kg of rhamnolipids are produced per batch. According to SuperPro Designer v8.5$^\text{®}$ evaluation, the fermentation process in Scenario I requires 52.8 h in the production stage starting from input of raw materials until the harvest of the fermentation broth (Table 1). Since this is the longest processing time out of all production steps, it can be concluded that one batch of fermentation can be produced every 52.8 h. Since one year has 7884 operation hours, it can be estimated that 149.2 batches of production can be performed per year. Rhamnolipids production per batch is calculated to be 2100 kg/batch. Thus, the annual production capacity for Scenario I is 313,330 kg rhamnolipids/year. The annual production capacity for each scenario can be calculated using Equation (3) as given below.

$$\text{Capacity}_x = \frac{7884}{t_x} \times 2100 \text{ kg RL per batch} \quad (5)$$

where $\text{Capacity}_x$ is annual production capacity in a specific scenario and $t_x$ is processing time per batch in a specific scenario (Table 1). The important correlation to note from Equation (5) is that when the processing time per batch decreases, the annual production capacity increases, thereby increasing the productivity and profitability.

3.2. Total Capital Investment

The value of total equipment costs and capital investment is outlined in Table S2 (Supplementary Materials). The total equipment cost is unit cost multiplied by the number of equipment used for each unit operation. It should be noted that there exists a difference in how these costs are calculated for upstream (fermentation) and downstream processes in this study. This can be explained as follows. Different scenarios assessed in the present study are based on the differences in the fermenter scale and its operating strategy since this affects the equipment downtime and hence the processing time for each scenario. In other words, the fermentation process in three scenarios is being changed. Consequently, the unit cost and total cost is different in different scenarios for fermentation processes. For example, Scenario I utilizes large-scale fermenters while Scenarios II and III utilize small-scale fermenters. Scenario II has the lowest total equipment cost due to the lower price of smaller-scale fermenters when compared to Scenario I and the usage of fewer fermenters when compared to Scenario III. Meanwhile, Scenario III utilizes the highest numbers of fermenters and thus, it has the highest total equipment cost among all the scenarios (see Table S2). On the other hand, the downstream operations are the same for all the scenarios i.e., using the same number of equipment for downstream unit operations.
in all scenarios. This is because all the scenarios have the same amount of rhamnolipids produced per batch of fermentation (only the annual production capacity is different due to the different processing time per batch in different scenarios). This means that there is no requirement to change the number of downstream equipment for various scenarios. Therefore, the unit cost and total cost remains the same in this case (Table S2).

For all the scenarios, the most expensive equipment is the freeze-dryer which constitutes about 25–27% of the total equipment cost. Overall, the equipment for downstream process in this study (including tank) comprises about 81–85% of total equipment costs. This is because the purification process is complicated and requires many steps to obtain pure product due to the low rhamnolipids titers and complexity of separation from other fermentation products such as proteins, lipids, salts, and other small molecules [30].

### 3.3. Rhamnolipids Production Cost, Revenue, and Profitability Analysis

The production cost includes raw material cost, labor cost, utility cost, and other general expenses (Table 2). Table 1 provides the details of the estimation method of production cost. Tables S3–S5 (Supplementary Materials) list the utility usage and costs, the annual operating hours and labor costs for each equipment in the process. The cost of raw material in this study constitutes about 10% of the total rhamnolipids production cost. Conventionally, raw material cost for rhamnolipids production can contribute to about 50% of the total production cost [31]. This is because the conventional substrates used in current rhamnolipids production i.e., hydrophobic substrates like vegetable oils, are expensive whereas raw and untreated food waste digestate used in this study was available for free due to policies on waste reduction by the Government of Hong Kong and cooperation with the Environmental Protection Department, Hong Kong. Another reason behind the low raw material cost was the hexane recyclability of 99%. On the other hand, the research and development costs for this study are approximated to be 3% of the revenue, which is on the high-end approximation according to Peters and Timmerhaus [19]. This is because rhamnolipids production from food waste digestate is still a relatively novel concept globally, thereby requiring more research efforts in the future. Similarly, since rhamnolipids is still an emerging bio-based entrant to the market, distribution and marketing costs were also estimated on the high-end of approximation at 14% of total product cost. Lastly, the depreciation contributes 15.8% of total production cost due to the large capital investment which frequently occurs in a new plant constructed on a new site.

### Table 2. Estimation of annual rhamnolipids production costs for each scenario.

| Category                              | Cost (USD) for Each Scenario |
|---------------------------------------|------------------------------|
|                                       | I               | II              | III             |
| Raw material cost                     | $2,394,826.55  | $2,095,076.89  | $2,530,852.69  |
| Utility                              | $1,644,548.23  | $1,464,007.31  | $1,725,799.68  |
| Operating labor                      | $508,989.02    | $743,096.77    | $897,660.89    |
| Direct supervisory and clerical labor | $76,348.35     | $111,464.51    | $134,649.13    |
| Maintenance and repairs              | $2,137,872.40  | $2,138,482.44  | $2,302,209.21  |
| Operating supplies                   | $320,680.86    | $320,772.37    | $345,331.38    |
| Laboratory charges                   | $76,348.35     | $111,464.51    | $134,649.13    |
| Patent and royalties                 | $677,401.49    | $656,644.41    | $745,229.64    |
| Depreciation                         | $3,563,120.67  | $3,511,603.04  | $3,679,416.21  |
| Local taxes and insurance            | $1,068,936.20  | $1,069,241.22  | $1,151,104.60  |
| Plant overhead costs                  | $1,633,925.87  | $1,795,826.23  | $2,000,711.54  |
| Administrative costs                  | $408,481.47    | $448,956.56    | $500,177.88    |
Table 2. Cont.

| Category                                  | Cost (USD) for Each Scenario |
|-------------------------------------------|------------------------------|
| Research and Development Costs            | I  | II            | III           |
|                                           | 4,229,961.75 | 3,700,525.77 | 4,470,227.99 |
| Distribution and marketing costs          | 3,161,206.95 | 3,064,340.58 | 3,477,738.31 |
| Contingency                               | 677,401.49  | 656,644.41   | 745,229.64   |
| Annual rhamnolipid production cost (RLPC) | 22,580,049.65 | 21,888,147.01 | 24,840,987.94 |
| Annual production capacity of 50% purity rhamnolipids (kg/year) | 626,661.00 | 548,226.04 | 662,256.00 |
| Selling price of 50% purity rhamnolipids syrup (per kg) | 225.00 | 225.00 | 225.00 |
| Annual revenue                            | 140,998,725.00 | 123,350,858.90 | 149,007,599.70 |
| Gross profit                              | 118,418,675.35 | 101,462,711.89 | 124,166,611.72 |
| Net profit                                | 99,467,508.83  | 84,721,364.43 | 104,286,224.46 |
| Minimum selling price of 50% purity rhamnolipids (per kg) | 36.03 | 39.93 | 37.51 |
| Cumulative net present value (NPV)         | 650,138,355.00 | 550,959,551.42 | 682,447,441.37 |
| Internal rate of return (%)                | 60.1 | 54.7 | 60.8 |

Annual revenue was calculated by multiplying the rhamnolipids selling price with the annual rhamnolipids production capacity. It is important to emphasize that although Scenario I has twice the size of fermenters compared to Scenarios II and III, all three scenarios have same total working volume of fermenters (for Scenarios II and III, total working volume equals to $2 \times 175 \text{ m}^3 = 350 \text{ m}^3$ in production stage). The important difference between these three scenarios is in the optimization of production scheduling and minimization of equipment downtime, which consequently increases the annual production capacity, thereby increasing the annual revenue.

The profitability analysis was performed by calculating gross profit, net profit, minimum selling price, cumulative net present value (NPV), and internal rate of return (IRR). The results of profitability analysis are summarized in Table 2. In addition, cumulative NPV diagrams over the plant’s lifetime were calculated and are illustrated in Figure 3. It was found that all three scenarios were profitable, as indicated by their positive IRR values (Table 2). The most profitable scenario is Scenario III with the highest IRR of 60.8%. The lowest minimum selling price is for Scenario I, i.e., USD 36.03 per kg rhamnolipids. Scenario III is the most profitable process since it has the highest annual rhamnolipids production capacity, compared to Scenarios I and II which can be attributed to the smaller downtime of fermenters used here. From these comparisons, it can be concluded that the profitability and IRR increase with higher annual production capacity. Higher productivity can be achieved by reducing the processing time per batch. One method to reduce the processing time per batch is by reducing the downtime of equipment via utilization of multiple smaller-scale fermenters to efficiently arrange the scheduling of equipment usage.
3.4. Sensitivity Analysis

The sensitivity analysis was performed by varying important factors in this process and analyzing their effects on economic performance of the rhamnolipids process. Since this plant effectively solves the digestate waste problem in Hong Kong, the government might also give the plant a ‘digestate treatment service fee‘, thus providing the plant with additional source of revenue. Currently, since the sale of rhamnolipids is the sole source of revenue for the process, sensitivity analysis on the selling price of rhamnolipids was performed. The IRRs from each varying factor were compared to determine the most influential factor affecting the economic performance. Table 3 (a) shows the effect of digestate price and rhamnolipids price on process profitability. It can be inferred that variation on digestate price only slightly affects the profitability since the digestate is valued at a low price, i.e., USD 0.006/L, according to the Waste and Resources Action Programme [4]. On the other hand, variation on rhamnolipids price largely influences the profitability since the revenue was generated only from selling rhamnolipids.

Figure 3. Cumulative net present value (NPV) diagram at different discount rates of 0%, 7% and 15% in (a) Scenario I, (b) Scenario II and (c) Scenario III.
Table 3. Sensitivity analysis of different variables on process economics. (a) Effect of cost of digestate and rhamnolipids selling price. (b) Impact of different annual production capacity. (c) Influence of percentage of hexane recyclability and land rent cost.

(a) Effect of cost of digestate and rhamnolipids selling price.

| Cost of Digestate (USD/L) * | Cumulative NPV     | IRR   |
|-----------------------------|--------------------|-------|
| −0.012                      | $652,906,409.43    | 60.30%|
| −0.006                      | $651,522,382.22    | 60.20%|
| 0                           | $650,138,355.00    | 60.10%|
| 0.006                       | $648,754,327.79    | 60.10%|
| 0.012                       | $647,370,300.58    | 60.00%|

| Selling price of 50% rhamnolipids (USD/kg) | Cumulative NPV     | IRR   |
|-------------------------------------------|--------------------|-------|
| 70                                        | $78,074,340.60     | 7.10% |
| 120                                       | $262,611,194.44    | 32.00%|
| 175                                       | $472,521,705.37    | 49.00%|
| 200                                       | $561,330,030.19    | 54.80%|
| 225                                       | $650,138,355.00    | 60.10%|
| 250                                       | $738,946,679.82    | 65.10%|
| 275                                       | $827,755,004.64    | 69.70%|

(b) Impact of different annual production capacity.

| Annual Production Capacity (%) | Cumulative NPV     | IRR   |
|-------------------------------|--------------------|-------|
| 80                            | $505,914,883.23    | 54.40%|
| 90                            | $577,934,305.30    | 57.50%|
| 100                           | $650,138,355.00    | 60.10%|
| 110                           | $722,502,713.66    | 62.60%|
| 120                           | $795,008,175.09    | 64.80%|

(c) Influence of percentage of hexane recyclability and land rent cost.

| Hexane recyclability         | Cumulative NPV     | IRR   |
|------------------------------|--------------------|-------|
| 99% hexane recycled          | $650,138,355.00    | 60.10%|
| 75% hexane recycled          | $595,281,052.49    | 56.90%|
| 56% hexane recycled          | $551,825,354.66    | 54.20%|
| 50% hexane recycled          | $538,138,029.03    | 53.30%|
| 25% hexane recycled          | $480,995,005.17    | 49.50%|
| No hexane recycled           | $448,227,494.97    | 54.20%|

| Land rent cost               | Cumulative NPV     | IRR   |
|------------------------------|--------------------|-------|
| Paid rent for land           | $650,138,355.00    | 60.10%|
| Rent-free land               | $651,717,090.95    | 60.80%|

* The cost of digestate is USD 0.006/L [4].

It is also possible that the plant does not operate at full capacity throughout the production year due to scheduled maintenance, inventory management errors, possible equipment failure, or other unforeseen circumstances. It was previously mentioned that the annual production capacity directly affects the profitability. Therefore, it is also important to perform a sensitivity analysis to determine the effect of average yearly production capacity on profitability. Table 3 (b) shows the effect of different annual rhamnolipids production capacity on IRR. Changes in annual rhamnolipids production capacity largely...
affect the profitability. This sensitivity analysis is consistent with the results shown in Table 2 where increase in rhamnolipids productivity shows an increase in profitability of the process.

Since raw materials (other than digestate) also constitute a large fraction of the production cost, hexane recyclability can also affect the profitability of the process. Currently, it is assumed that 99% of hexane is recyclable. If 0% hexane is recyclable, a distillation tower is also not required and thus will not be included in the calculation of the total capital investment (TCI). Lastly, as previously mentioned, it is possible to obtain rent-free land in Hong Kong due to the government support for processing of wastes. Table 3c shows the sensitivity analysis on hexane recyclability and rent cost of land. There is a minimum hexane recyclability in order to justify the investment in building a distillation tower. This is because at 0% hexane recyclability, there is no need to build a distillation tower, as explained above. The minimum hexane recyclability is 56%, where the IRR reaches a similar value as in the case of 0% hexane recyclability (54.2%). Furthermore, hexane recyclability can reduce the IRR until 49.5% when only 25% hexane can be recycled. On other hand, sensitivity analysis on rent-free land only increases the IRR by 0.7%, which is not very significant from an economic perspective.

3.5. Comparison with Previous Work in Literature

Few similar studies on techno-economic assessment of biosurfactants have recently been performed. Wang et al. evaluated the techno-economic feasibility of sophorolipids production from food waste using the yeast *Starmerella bombicola* [12]. Similarly, another study was performed to produce surfactin and lichenysin using minimal medium by bacteria *Bacillus subtilis* and *Bacillus licheniformis* [32]. Minimal medium is a pure substrate comprising of expensive synthetic nutrients. On the other hand, the process by Wang et al. uses food waste which is an inexpensive and abundantly available organic waste material. In this regard, it is similar to the present study which also uses a waste feedstock. However, important differences exist between the present study and the previous one by Wang et al., which are as follows. First, this study utilizes food waste digestate as a feedstock for the production of rhamnolipids whereas Wang et al. used food waste in their process. For using food waste, it needs to be converted into the hydrolysate form using some form of pretreatment step, e.g., enzymatic treatment used by Wang et al., to convert the complex organic matter into simple sugars (glucose), nitrogen and phosphate sources which can then be used as the fermentation medium. This additional pretreatment step incurs an additional cost on the overall production process. On the contrary, the process in the present study being based on food waste digestate does not require any pretreatment to solubilize the organic matter and the digestate can be directly used as the fermentation medium. This reduces the overall process cost of this process. Additionally, pure nutrients in the form of refined glucose and oleic acid were also added in the process of Wang et al. while no additional expensive and/or pure substrates are added in the process in the present study. Secondly, although both the studies are based on biosurfactant production, the type of biosurfactant produced and the producer microorganism is different, i.e., the present study produces rhamnolipids from a bacterial producer with a much shorter cultivation time, while Wang et al., produced sophorolipids using a yeast producer requiring a longer cultivation time.

In terms of advances in biosurfactant production, the present study developed a new process for rhamnolipids biosurfactant using food waste digestate as the sole substrate and demonstrated its economic feasibility. To the best of the authors’ knowledge, such a biotechnological process based on digestate has not been reported for biosurfactants so far and, therefore, the present study contributes significantly to advance the research on biosurfactants.
4. Conclusions

Techno-economic assessment of rhamnolipids production from food waste digestate was performed and three scenarios were considered in this study. From the IRR analysis and cumulative NPV graphs, it is recommended to establish optimum scheduling of equipment and utilize multiple small-scale equipment to reduce the downtime of each equipment in order to increase the productivity. Most importantly, this study showed that rhamnolipids production from food waste digestate is a promising and profitable process with the highest IRR of 60.8% in Scenario III. Current sensitivity analysis also showed that the most influential factors were rhamnolipids price, production capacity as well as hexane recyclability.

It should however be noted that although the current market price of rhamnolipids is high, a lower value is required to enable higher market penetration. Such high market price implies lower volumes of product entering the market, which would again increase the product price. With the improvements in process productivity, the rhamnolipids volumes could be increased, which would result in a lower market price based on the principles of economies of scale. Therefore, it is necessary to sell rhamnolipids at lower prices in order to allow greater market penetration when high production volumes are reached.

Other important considerations are the yield of rhamnolipids and recovery from purification processes and their impact on process economics. Thus, the future investigations on techno-economic assessment should consider variables such as rhamnolipids yield, recovery efficiency and selling price to provide a more detailed analysis.

Supplementary Materials: The article contains the following Supplementary Material. Table S1. Annual operating hours for each equipment for Scenario I, II and III, Figure S1. Examples of rhamnolipids structures. (A) Mono-rhamnolipids and (B) Di-rhamnolipids, Table S2. Estimation of total equipment costs and total capital investment for each scenario, Table S3. Estimation of utility usage in each operation, Table S4. Estimation of labor cost in each operation, Table S5. Summary of operating hours, temperature, utilities cost, and labor cost in each operation.

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