Biological Conversion of Organic Municipal Solid Waste to Lactic Acid: A Techno-Economic Performance Assessment Study for Commercialization

by

Jieun Shin

B.Eng., University of Tokyo (2012)

Submitted to the Institute for Data, Systems, and Society
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Author .... Signature redacted ....
Institute for Data, Systems, and Society
August 11, 2017

Certified by........ Signature redacted ....
Gregory Stephanopoulos
W.H. Dow Professor, Chemical Engineering
Thesis Supervisor

Accepted by .... Signature redacted ....
Munther Dahleh
W. Coolidge Professor, Electrical Engineering and Computer Science
Director, Institute for Data, Systems, and Society

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Abstract

This thesis assesses the economic viability and commercial potential of a lab-scale microbial technology to produce lactic acid (LA), which was developed as a novel technology option for organic waste treatment. Among various available technologies for the separation and purification of LA, the method of esterification-hydrolysis with reactive distillation was selected for this assessment. The process from organic waste to high-purity LA was designed and modeled using Aspen Plus, from which material and energy balances, equipment costs, and utility costs were derived. An economic performance assessment model was developed to estimate capital and operating expenses as well as net present value (NPV), for evaluating the economic feasibility under various scenarios. Monte Carlo techniques were incorporated into the model to take into account the effect of identified uncertainties on the economic performance, which generates distribution profiles rather than single-value estimates. The baseline NPV for polymer-grade LA (99%) production was estimated to be USD 1.95 million in the U.S. and USD 1.31 million in India. Even though the estimated capital and operating expenses are much lower in India, the process was found to be less profitable than in the U.S. The main reason for this is because landfill tipping fees cannot be relied on as a stable revenue source in India. Moreover, two other applications, which this technology could be potentially commercialized for, were also evaluated using the developed models, and the economic performance of each application was compared. Finally, this thesis proposes a Technology Commercialization Assessment Matrix (TCAM), based on the results and insights gained from the assessment conducted.

Thesis Supervisor: Gregory Stephanopoulos
Title: W.H. Dow Professor, Chemical Engineering

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Chapter 1

Introduction

The need to overcome the dual challenges that our current global society faces, resource depletion and waste accumulation, has led to the development of various waste treatment technologies. The utilization of waste as a feedstock to produce a high-value chemical, such as lactic acid (LA), is one example of a technology-based solution to help reduce the cost of raw materials while reducing the environmental impact caused by current waste disposal practices. The laboratory of Professor Gregory Stephanopoulos (Department of Chemical Engineering) at MIT has developed a novel microbial technology based on anaerobic digestion of organic waste for LA production [63]. In order to scale-up and commercialize this lab-scale technology, a series of questions should be answered. These include: (1) What are the potential applications of LA and the required product specifications for these applications?; (2) How can these specifications be achieved, specifically the purity of LA? In particular, what is the most economical way to separate and purify the crude LA from the initial fermentation?; (3) How can the overall processes be designed to obtain a desired purity of LA?; (4) What are the costs associated with a LA production facility?; (5) How much does it cost to produce LA from organic waste?; and (6) What is the profitability of this production method?

This research examines the technical and economic feasibility of producing polymer-grade LA (99% purity) from organic waste, by conducting a techno-economic assessment. To that end, this study first compared available technologies for the separation and purification of LA to determine the most economically feasible method. Further, process design and simulations were conducted using Aspen Plus to determine material and energy balances, as well as equipment sizes and costs. Based on the results of the process modeling effort, the key economic costs, including the Fixed Capital Investment (FCI), Total Capital Investment (TCI), and Total Product Cost (TPC) were estimated under various economic scenarios. Additionally, a detailed comprehensive Net Present Value (NPV) model was also developed to evaluate the economic profitability. In the estimation of both the economic costs and the NPV, various sources of market and regulatory uncertainty were identified and their effect on the economic performance has been taken into consideration using Monte Carlo simulations. Using the developed models, sensitivity and comparative analyses were conducted to investigate how various scenarios affect the economic performance. Lastly, based on the results and insights gained from the assessment, a Technology Commercialization Assessment Matrix (TCAM) is proposed, which should serve as a guideline for conducting further economic assessments or developing investment strategies for technology commercialization.

The remainder of this thesis is broken out as follows. Chapter 2 provides the background on municipal solid waste (MSW) management in the United States and India, as well as the current state of LA applications and production methods. Chapter 3 describes the process design of the waste-to-LA plant and the details of the model. Chapter 4 describes the economic model and the assumptions used for evaluating the economic costs and profitability of the plant. Chapter 5 presents the results of the economic performance assessment and the sensitivity/comparative analyses, and further discusses investment strategies to scale-up and commercialize this microbial technology in India. Chapter 6 summarizes this thesis work, major findings, and makes suggestions for future work.

Chapter 2

Background

2.1 Municipal Solid Waste Management

Municipal Solid Waste (MSW) is a type of waste generated from residential and commercial sources, which consists of everyday items such as food scraps, garden waste, paper, textiles, product packaging, and bottles. Although the composition of MSW varies from region to region, organic waste accounts for a large share of MSW both in developed and developing countries. Uncontrolled decomposition of organic MSW poses risks to both the environment and public health through the contamination of soil, water, and air. As a result, effective and proper management of the organic fraction of MSW is a global issue of great importance.

When one metric ton of organic waste decomposes in landfills, which continues to be the primary means of waste disposal, 50-110 m^3 of carbon dioxide and 90-140 m^3 of methane can be potentially emitted, contributing to global warming [44]. According to the Intergovernmental Panel on Climate Change (IPCC), methane (CH_4) is estimated to have a Global Warming Potential (GWP) 25 times higher than carbon dioxide (CO_2) for a 100-year time scale [51]. Moreover, the leachate (the liquid that percolates through the layers of waste, absorbing toxic chemicals) contaminates ground water at landfill sites, which can in turn impact local water supplies [15].

Governments and municipalities are beginning to recognize the importance of reducing the quantity of organic waste sent to landfills. Consequently, various programs have been adopted, including those to address the source of waste and to handle the waste that has already been generated. On the front-end, reductions in the total tonnage entering into a given municipal waste system can be achieved by promoting changes in purchasing habits, package design, industrial practices, as well as promoting home composting and reuse [16]. Secondly, the waste that has already been generated can be converted into useful products, such as reusable materials, compost, and energy, for waste diversion. The overall effect is, when properly implemented, a radical reduction in landfilling.

During the last century, developed countries have established appropriate standards as well as devoted adequate administrative and financial resources to manage MSW in an economical and environmentally sound manner [52]. In addition, innovative technologies have received increasing attention to recover materials and create economic value from MSW, which would otherwise be landfilled. On the other hand, in developing countries, MSW management has become a fundamental socio-economic problem, as these nations lack the capacity to effectively handle the increasing volume of MSW, due to insufficient capital, knowledge, and infrastructure. As the solid waste problem is not merely a domestic issue, knowledge and technology transfer from developed countries to developing countries is crucial in order to accelerate global sustainable development.

2.1.1 The United States

According to an EPA report, the total quantity of MSW generated in the U.S. was 258 million tons per year as of 2014. Of this waste, only 34.6% of the waste generated was recycled or composted [16]. While the total amount of MSW generated has almost tripled since 1960, the recycling and composting rate has also considerably increased in the U.S. from 6.4% in 1960 to 34.6% in 2014, with a significant improvement especially during 1985-1995 (see Figure 2-1). This change was the result of increasingly stringent standards for MSW management facilities under the Resource Conservation and Recovery Act (RCRA) of 1976, which is the principal legislation that governs the management of hazardous and non-hazardous solid waste in the

United State [41]. The RCRA Subtitle D provides specific guidelines for the proper management of MSW, mandating the closure of open dump sites across the country as well as setting minimum requirements for the operation of landfills. Further, states and municipalities play an important role in executing the federal guidelines and further establishing stricter rules.

Despite these continuous federal and regional efforts, more than half of the total MSW generated still goes to landfills [16]. Among various materials included in MSW, 14.9% of the total quantity of MSW was food waste, which is the main contributor of greenhouse gas emissions from landfills. Further, it was reported that 76% of food waste was landfilled, while 19% was converted into energy through incineration and only 5% was recycled and composted as of 2014 (see Figure 2-2). Therefore, new financially compelling technologies/systems still need to be developed and implemented to maximize the quantity of food waste diverted from landfills. Among the currently available technology options described in Section 2.2, anaerobic digestion (AD) is considered to be the most environmentally-friendly practice to treat and create value from food waste. In the U.S., over 2,200 major biogas production facilities are in operation; nevertheless, most of them are a part of wastewater treatment plants, rather than standalone anaerobic digesters [38]. Despite a large biogas potential in terms of feedstock supply, the U.S. has been slower to implement this technology compared to Europe, where nearly 17,000 biogas plants produce energy equivalent to 14.9 Mtoe in total [38, 46]. According to the US Department of Energy, there are over 13,000 potential sites that could implement a biogas production system in the U.S., which could provide over 40 TWh of electricity [48].

2.1.2 India

In India, the annual quantity of MSW generated has significantly increased over the past 50 years, a trend which is expected to continue due to urbanization, population growth, and industrialization. According to a Planning Commission report, it was estimated that people in urban areas generate approximately 62 million tons of MSW every year, based on census data from 2011 [12]. Further, it is projected that the

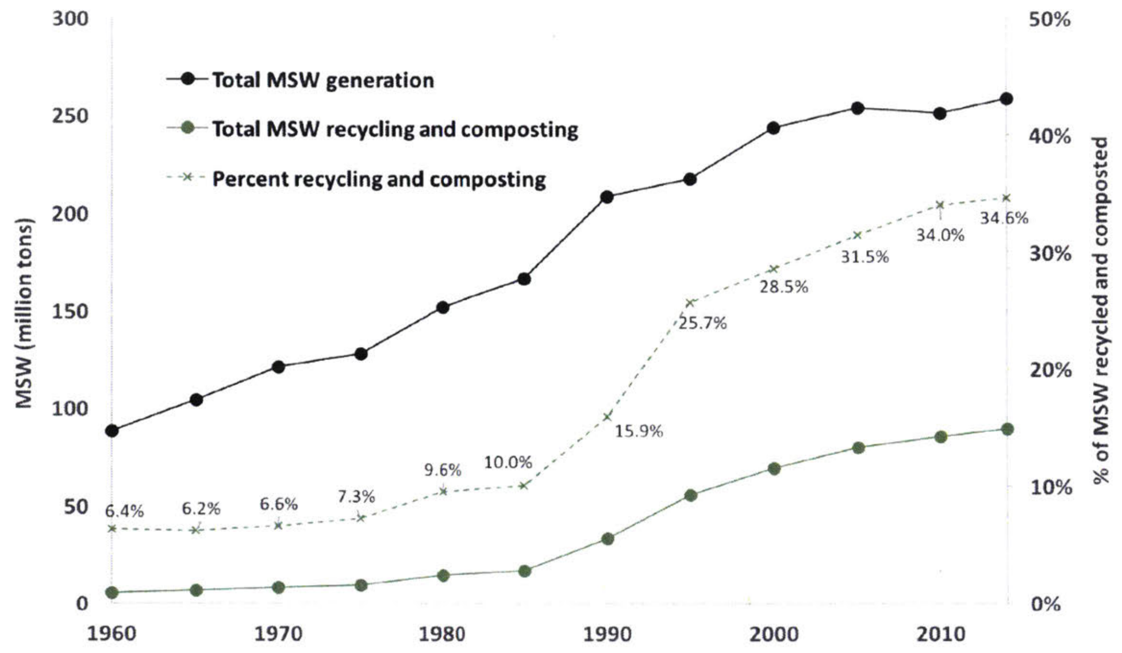


Figure 2-1: MSW generation and recycling rates in the United States, 1960-2014. Source: [16]

quantity of MSW in urban centers will reach 165 million tons by 2031, and increase sevenfold (436 million tons) by 2050 [12]. In contrast to developed countries, Indian Federal or State regulations have not caught up with this rapidly intensifying problem. Given that the management of MSW is not effectively executed, India set up specific guidelines for MSW management through Municipal Solid Waste (Management and Handling) Rules, 2000 (MSWR). These guidelines were then updated in 2016 by the enactment of the new Solid Waste Management Rules (SWM), 2016; nevertheless, many municipalities have not effectively implemented these practices and are not in compliance with them [37]. As a result, only 70% of the total waste generated is collected in Indian cities and states, due to the lack of systematic storage space at the source and low awareness among the waste generators [20, 37, 62]. Further, out of the total MSW collected, about 93-94% is disposed of through uncontrolled landfilling or open dumping without appropriate precautions to avoid environmental contamination, with the remainder being converted to compost [20, 30]. Consequently, most Indian cities have faced environmental degradation as well as unhygienic conditions

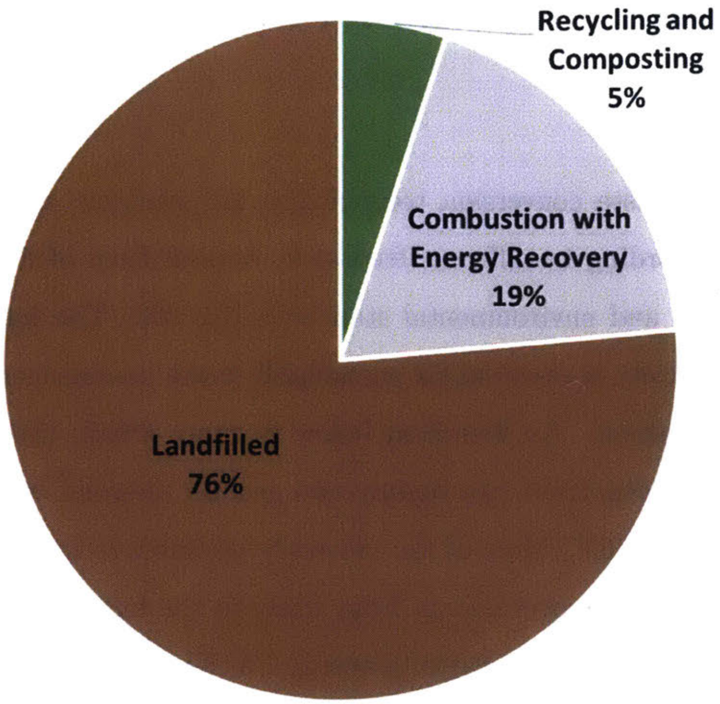


Figure 2-2: Management of food waste in the United States, 2014. Source: [16]

at the disposal sites.

Waste-to-energy systems, such as incineration and biomethanation, have been introduced as a value-added mechanism for waste disposal in India, but adoption has remained low [20]. In contrast to developed countries, the economic viability and sustainability of the waste-to-energy systems are still being examined in India, as the country faces unique challenges in adopting these technologies. The hurdles include a lack of financial resources, insufficient technical expertise, and a dearth of the required machinery [37, 60]. Among various waste-to-energy technologies, anaerobic digestion has shown great potential in India, both in regard to its use as a waste treatment option and as a renewable energy source. A major reason for this observation is the larger proportion of biodegradable matter in Indian MSW, which accounts for 40%-60% of available MSW [20, 37].

2.2 Technology Options for MSW Treatment and Utilization

Various types of waste conversion technologies are available and need to be chosen/combined according to different feedstock, desired form of final products, economic conditions, and environmental standards [12, 32]. The integration of these technologies in society is essential for sustainable waste management as well as profitable waste utilization. As described below in more detail, the waste conversion processes can be categorized into mainly two groups: thermal conversions and biochemical conversions [69]. Most of the currently available technologies in both categories are designed to recover energy from waste in the form of electricity, heat and fuel, which are grouped under waste-to-energy (WtE) technologies [12].

2.2.1 Thermal Conversion

Thermal conversion processes of MSW can be divided into three main categories: incineration, pyrolysis, and gasification. Thermal processing is the only solution that can handle unsegregated (mixed) waste streams; nevertheless, it can be challenging to avoid unfavorable environmental impacts as well as high startup costs.

Incineration

Incineration is the combustion of solid waste in a controlled manner at 850 ^oC in the presence of sufficient air to oxidize feedstock. This exothermic process generates heat, which can be utilized in the form of steam or electricity. Incineration has been the primary alternative to landfills primarily due to its ability to reduce waste mass by 70% and volume by 90% [61]. However, air pollutants such as SO_x, CO_x, and NO_x are emitted during the process, which contribute to air pollution and pose significant health hazards. Thus, when constructing an incinerator, pollutant-capturing devices have to be installed to reduce these problems. Further, low moisture content and high heating value of solid waste are desirable to achieve high level of efficiency. This is the reason why incineration is not popular in developing countries such as India where a large amount of organic waste is generated, which has a high moisture content (~20%) and fairly low heating value [66].

Pyrolysis and Gasification

Both pyrolysis and gasification generate energy by combusting solid waste under oxygen deficient conditions. Pyrolysis uses thermal energy to degrade organic matter at a temperature range of 400-1000 ^oC in an oxygen-free environment [69]. On the other hand, gasification is the partial combustion of organic materials at higher temperatures than pyrolysis (1000-1400^oC) in a limited amount of oxygen. The end product of these two endothermic processes is syngas, which is a mixture of CH_4, CO and H_2, with lesser amount of CO_2, N_2 and hydrocarbons(HCs). Syngas can be used for heat and power production, by means of internal combustion engines or turbines [62]. According a life cycle assessment conducted by Zaman, pyrolysis-gasification is the most environmentally-friendly technology among thermal conversion processes in terms of global warming, acidification, etc., due to its high efficiency of energy recovery [69]. However, the main limitation of pyrolysis-gasification is that the process is complex and requires higher capital and operation costs than incineration.

2.2.2 Biochemical Conversion

Biochemical conversion processes are considered to be much more eco-friendly than the thermal treatment options discussed above [32, 61]. This category consists of mainly two techniques: anaerobic digestion (i.e. biomethanation) and composting, both of which involve the degradation of organic materials into valuable products catalyzed by microorganisms. As opposed to incineration, high percentages of organic matter and moisture are preferred for the biochemical conversion processes to boost microbial activity.

Anaerobic Digestion

In anaerobic digestion (AD), the organic fraction of MSW is fed to an anaerobic digester where microorganisms break down organic matter in the absence of oxygen. This process produces biogas (primarily CH_4 and CO_2) as the main product, which can be used either as a heat source or for electrical generation. Additionally, the material that remains after organic materials are completely digested (called digestate) also has a use as a soil conditioner which helps maintain moisture and organic content in soils. Simultaneously, it replenishes various minerals which are depleted during the harvesting of crops. With this concept in common, there are a variety of engineered bioreactors to treat organic waste, which can be classified by different factors such as operating temperature, solids content in the reactor, one or multiple phases, and method of mixing and agitation [39]. This waste treatment option is increasingly gaining popularity globally, as it can address environmental problems caused by MSW and simultaneously produce biogas, which is a carbon neutral and comparatively clean energy source relative to fossil fuels. Further, the fact that AD requires a low energy input and can be accommodated in smaller reactors adds to its advantages. However, a disadvantage of this process is that it requires longer start-up and retention time (>3 weeks) to obtain stabilized products, compared to other biological processes [2].

Composting

Composting is an aerobic biological process during which decomposition of organic waste takes place by microbial activity under controlled conditions, including temperature, humidity and pH [62]. This converts organic waste to stable granular material (i.e. compost) - which can be used as an organic fertilizer and soil conditioner [55]. Composting is widely used both in large scale and at decentralized level as one of the most cost effective options for MSW management; nevertheless, it has several limitations. First, a great deal of energy is released into the atmosphere during aerobic composting, which results in heat loss to the surrounding environment. Further, the quality of compost generated from MSW can vary depending on a number of factors, including the characteristics of organic waste and composting procedures employed. It should be noted that compost is different than chemical fertilizer which is enriched in terms of nutrient value, although both play important roles in agriculture. Lastly, this treatment requires careful separation of MSW prior to composting, as toxic materials such as heavy metals might be introduced into human food chain [32].

2.3 Lactic Acid

Lactic acid (2-hydroxypropanoic acid) with two enantiomeric forms (L-(+)-lactic acid and D-(-)-lactic acid) is a platform chemical from which a wide range of useful products are derived. Due to various potential applications, the global demand for LA has been estimated to increase from USD 1,130.4 million in 2014 to USD 3,381.8 million in 2023, growing at a a compound annual growth rate (CAGR) of 13.0% [56].

2.3.1 Applications of Lactic Acid

Lactic acid (LA) has been widely used in food, pharmaceutical and cosmetic applications, since its discovery in 1780 by the Swedish chemist Scheele. Traditionally, the food industry has been the major consumer of LA, demanding approximately 70% of its global production capacity [9]. Its mild acidic taste as well as nonvolatile and odorless properties allow LA to be used as an acidulant, preservative, flavoring, and pH buffering agent in processed foods. The primary application of LA in foods is to produce esters of lactate salts with longer chain fatty acids, which are used as emulsifiers to improve the consistency and texture of foods [14]. Moreover, due to the moisturizing, antimicrobial and rejuvenating effects of LA, it has been one of the popular ingredients used in the formulation of cosmetics and personal care products. Numerous pharmaceutical processes also use LA and its salts, mainly as a pH-regulator, chiral intermediate, and for metal sequestration [3, 53].

Nevertheless, the significant recent growth of the LA market has mainly come from the development and commercialization of LA-derived biopolymers - primarily poly-lactic acid (PLA). Owing to the presence of two functional groups, one hydroxyl and one carboxyl groups, LA undergoes versatile chemical reactions such as condensation and esterification, through which a variety of useful industrial products are obtained. Such products include biodegradable polymers for plastics and fibers, 'green' solvents for formulations and cleaning, and oxygenated industrial chemicals [14]. In particular, PLA, a biodegradable thermoplastic derived from 100% renewable resources, has received great attention as a potential substitute for petroleum-based plastics. This is in response to increasing demands for environmentally-friendly products, as well as the increasing scarcity and price volatility of fossil sources.

2.3.2 Production Technologies

LA is commercially produced either by chemical synthesis from fossil resources, or by microbial fermentation of carbohydrates. While the former route results in a racemic mixture of LA, the latter method can generate a desired enantiomer, optically pure L-(+)- or D-(-)-lactic acid [7, 68]. Additionally, LA production through fermentation has been shown to be more eco-friendly, due to low energy consumption as well as the ability to utilize relatively cheap renewable feedstock such as agricultural and agro-industrial based raw materials [19]. As a result, almost all of the present LA manufacturers use the fermentative production route. The major LA producers include NatureWorks LLC (USA), Purac (The Netherlands), Galactic (Belgium), as well as several Chinese companies [1].

In LA fermentation, the cost of conventional feedstocks - pure sugars and food crops - accounts for a significant proportion of the LA production costs, which has motivated the search for low-cost raw materials as well as technology development for productivity enhancement. For more economically competitive processes, the use of non-food carbohydrates (e.g. cellulose and hemicellulose from lignocellulosic biomass) have been investigated as a replacement for traditional feedstocks, which has been partially successful [9]. Further, in recent years, genetic-engineering approaches have been harnessed to explore various combinations of metabolic pathways by microorganisms, which could lead to not only higher LA yield and productivity, but also broader substrate range and enhanced optical purity [1].

Separation and Purification Options for Lactic Acid

It is a well know fact that the separation and purification of LA from fermentation broth is a difficult and expensive process, which typically accounts for 50-70% of total production costs. This downstream process is crucial to achieve a targeted purity, by removing a number of impurities contained in fermentation broth. In particular, the highest purity level (99%) is required for the production of polymer-grade LA, which is the starting material for PLA synthesis. As the non-volatile nature of LA does not allow the application of conventional purification methods such as distillation, various technologies have been developed to recover LA in a more economical and efficient manner [36]. The main purification methods include esterification-hydrolysis with reactive distillation ([35, 36, 64]), reactive extraction ([22, 31, 67]), electrodialysis ([21, 34, 40]), and ion-exchange methods ([11, 19]. According to a comparative assessment conducted by Joglekar et al. [29], the most economical and practical option is esterification-hydrolysis with reactive distillation, which was selected for the scope of this project. As described in more detail in Chapter 3, this method first converts LA to the relatively volatile ester by the reaction with alcohol, which is followed by hydrolysis of the separated ester back to LA.

Chapter 3

Plant Design and Simulation

The potential waste-to-LA process for producing polymer grade LA can be roughly divided into three stages: fermentation, crude separation, and purification. Figure 3-1 shows an overview of the process from the feedstock to the final product of 99% LA, which was designed based on the process information provided in a number of studies [4, 5, 29]. Among the purification options for LA presented in the previous chapter, esterification-hydrolysis with reactive distillation was chosen as our model purification process, as it was considered to be the most economical and mature technology. The distillation process was designed and modeled using Aspen Plus (see Figure 3-2) with the goal of determining material and energy balances while estimating equipment and utility costs (a requirement for our ensuing economic analysis).

3.1 The Waste-to-Lactic Acid Process

The proposed waste-to-LA process, using the novel technology developed at MIT, ultimately aims to biologically convert organic waste into polymer-grade LA (~99 wt.% purity). This purity level is essential for the production of high quality PLA. First, preprocessed organic waste is fermented in an anaerobic digester over a certain period of time (frequently 5 days), which generates calcium lactate. As described in more detail below, LA is actively neutralized with a calcium base during fermentation. Calcium lactate is then reacted with sulfuric acid to yield crude LA and gypsum,

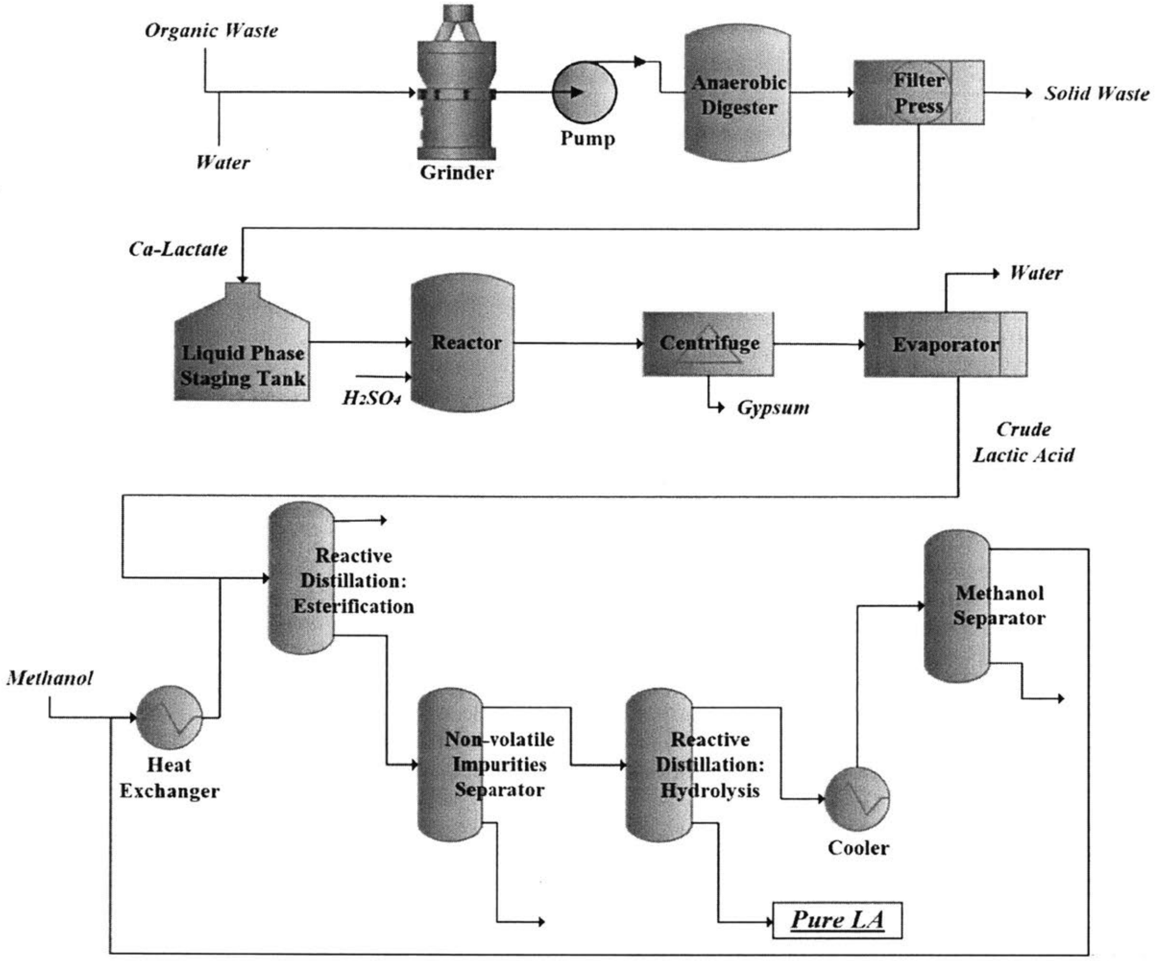


Figure 3-1: An overview of the process diagram

which is separated from the fermentation broth. Finally, after a large fraction of water has been removed using an evaporator, the crude LA goes through a series of reactive distillation columns and separators to eliminate impurities and raise LA purity up to ~99%.

3.1.1 Feedstock

The most ideal feedstock for the process is food waste, that is organic waste with high concentrations of sugar, starch, and protein. Although other organic waste such as agricultural waste can also be used, the solid retention time in the anaerobic digester is most likely to increase, resulting in reduced LA production from the feedstock

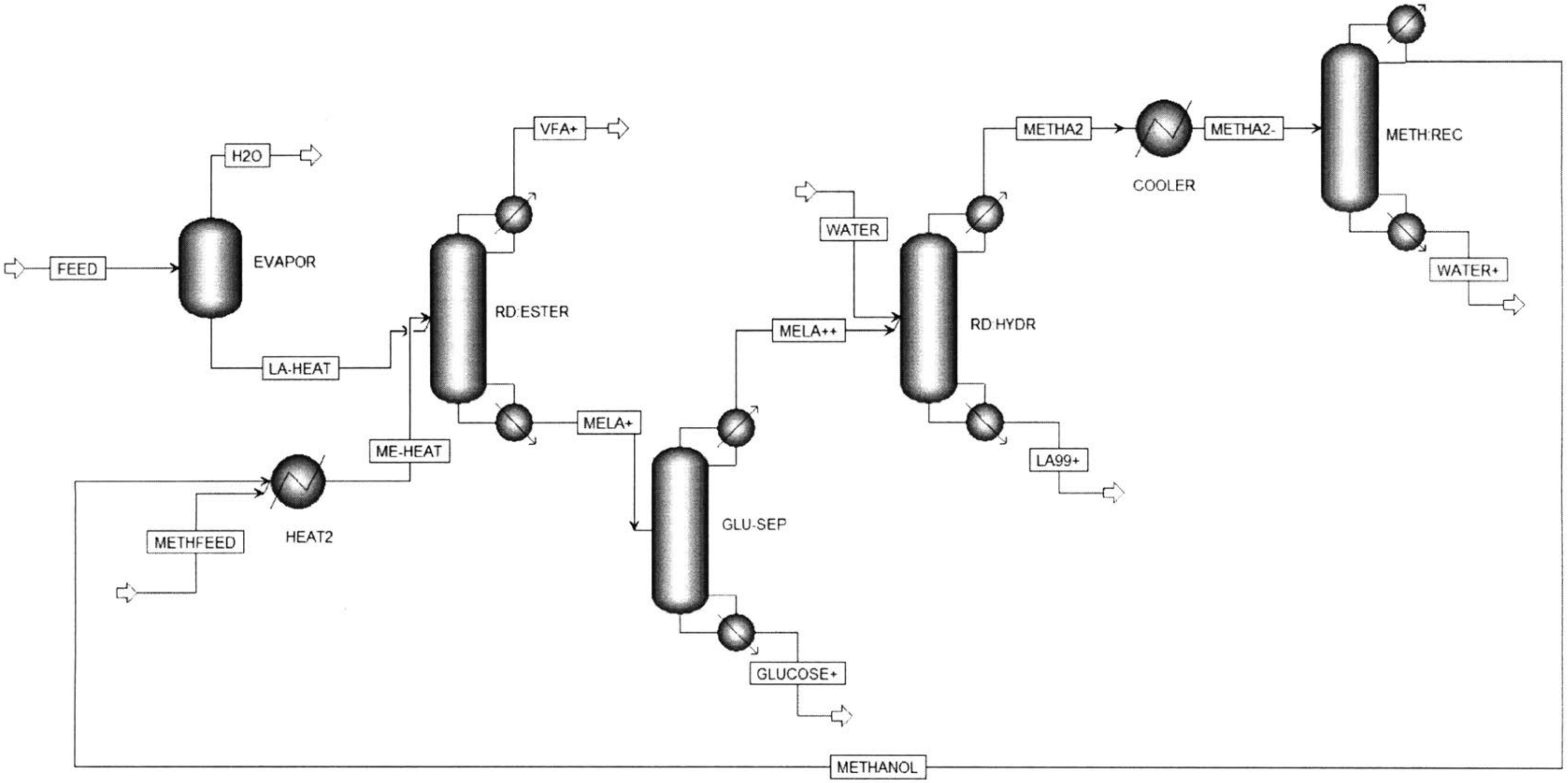


Figure 3-2: The process diagram from Aspen simulation

on a g/g/day scale. Lab-scale experiments conducted at MIT used a wide range of food waste collected on campus, including vegetables, fruit, bread, and meat, as well as their mixtures. For the baseline simulation, the total solids (TS) content of the feedstock was assumed to be 20 vol%, and the density of the solids was assumed to be 1 g/cm^3, based on experimental results. The feedstock is diluted with the same amount of distilled water to a TS content of 10 vol%, which is necessary for better initial mechanical disruption, mixing, heat transfer, as well as for improved metabolism [65]. However, if anaerobic digestion is operated under dry conditions, i.e. less water content, it possibly scales down reactor size and reduces energy consumption for separation systems [45]. This trade-off was examined by looking at the impact of the feedstock's TS content not only on the estimated utility cost but also on total capital and operating expenses, as demonstrated in Section 5.4.

3.1.2 Anaerobic Digestion

The diluted feedstock, after light homogenization with a grinding unit, is pumped into a fermentation reactor and allowed to ferment for ~5 days at a pH below 6.5 to avoid methanogenesis (the typical output of a bioreactor employing AD). In contrast to traditional bioreactors which often depend on a single organism, those developed for the fermentation of organic waste rely on a consortium of microbes, which is less likely to be affected by invading microbes with its ability to promptly adjust to changing environmental conditions [63]. Therefore, the fermentation method used for this waste-to-LA process does not require biological, chemical, or thermal sterilization, which is needed for other bioreactors to prevent the contamination of microbes. This reduces equipment and operation costs, as sterilization processes typically involve specialized equipment, skilled engineers, and stringent operating standards. Further, it has an additional advantage of preventing potential yield loss which may be caused by the contamination of microbes.

As mentioned above, a base such as calcium carbonate ($CaCO_3$) must be added to the fermentation broth, to alleviate pH inhibition. The production of LA lowers the level of pH in the reactor, which needs to be maintained to maximize growth rate [27]. Either strong acidic or alkaline environment can impede the metabolism of organisms and disrupt various aspects of their physiology. By adding $CaCO_3$, LA is converted into calcium lactate ($CaLA_2$) according to the reaction shown in Figure 3-3, allowing the bioreactor to be held at a constant pH under the assumption of active monitoring and base addition. As $CaCO_3$ becomes more soluble with lower pH, the reaction does not start until the pH level falls below a certain level and a sufficient amount of $CaCO_3$ is dissolved. The complete anaerobic digestion leaves fermented sludge containing $CaLA_2$ and other impurities as the end product, after approximately five days.

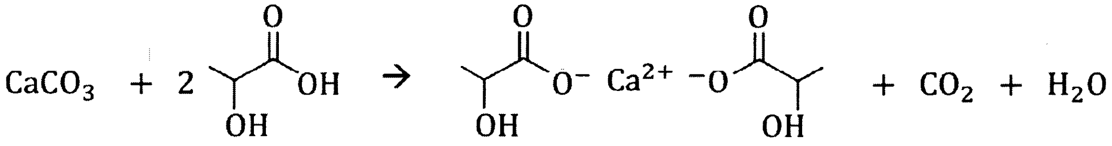


Figure 3-3: The reaction of lactic acid with calcium carbonate

3.1.3 Crude Separation of Fermentation Broth

The sludge obtained from the fermentation reactor needs to undergo a couple of separation steps, prior to esterification-hydrolysis with reactive distillation. First, the solids must be removed from the sludge; this will be most likely achieved with a filter press. Based on the experimental results shown in Table 3.1, the volume of remaining liquid was estimated to be 85,713 L per day, when 50 tons of organic waste are processed with 50 tons of water.

Table 3.1: The solid and liquid contents in fermented broth

Tube No.	Solid Mass / Broth Mass [mg/mg]	Liquid Volume / Broth Mass [µl/mg]
1	0.528	0.847
2	0.529	0.835
3	0.527	0.890
Average	0.528	0.857

In the following reactor, as in Figure 3-4, this liquid is acidified with sulfuric acid (H_2SO_4), which converts $CaLA_2$ back into LA and simultaneously generates a white solid precipitate ($CaSO_4$). Subsequently, $CaSO_4$ is separated out using a centrifuge, or potentially another filter press. This inorganic compound, commonly called gypsum, has a number of applications such as an additive of cement and plaster as well as a soil conditioner. However, no revenue from gypsum was assumed for this economic analysis due to the uncertain and unmeasured quality of the product. In the worst case, this material can be mixed with the compost stream composed of undigested solids that are separated out in the initial filter pressing.

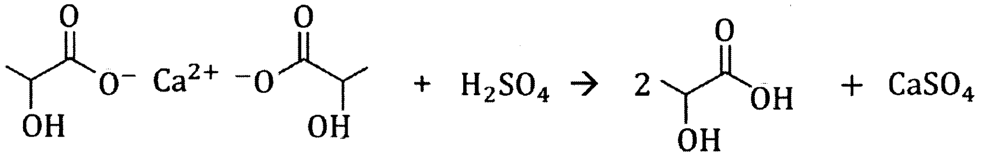


Figure 3-4: The reaction of calcium lactate with sulfuric acid

The resulting liquid contains water, LA, and other impurities including acetic acid, butyric acid, glucose, galactose, and pyruvic acid, as identified by experiments (DH Currie, personal communication). A large fraction of water is removed by an evaporator, prior to the purification process. Table 3.2 shows the concentrations of LA and impurities in a fermentation broth generated in an actual experiment. Among a number of fermentation broths tested, the most reasonable dataset was carefully selected not to overestimate the LA production. In calculating the mass balance, the assumptions were made that the solids would be completely separated by the filter press and centrifuge, and the conversion rate of $CaLA_2$ to LA would be 100%. Further, to simplify this simulation model, galactose and pyruvic acid were not taken into account as impurities, as their concentrations are much lower than acetic acid, butyric acid, and glucose.

Table 3.2: Concentrations of impurities contained in fermentation broth [g/L]

Lactic Acid	Acetic Acid	Butyric Acid	Glucose	Galactose	Pyruvic Acid
44.0	4.7	6.3	0.6	0.0488	0.134

3.1.4 Esterification-Hydrolysis with Reactive Distillation

As discussed in the previous section, esterification-hydrolysis with reactive distillation was used as a purification method for this assessment, since it is the most established and economical method identified [29]. Following the evaporator, the remaining liquid stream is transferred to the first reactive distillation column, where LA is esterified with methanol to produce methyl lactate (see the reaction equation in Figure 3-5). As LA is practically non-volatile, this conversion is necessary to make the distillation and separation of impurities feasible. This esterifiaction reaction is equilibrium limited; nevertheless, a near 100% conversion can be achieved by simultaneously removing methyl lactate and water from the column. Similarly, both acetic acid and butyric acid are also esterified with methanol, generating methyl acetate and methyl butyrate. Along with these reactions, the first distillation column continuously removes the volatile components which have lower boiling points than methyl lactate from the top. Table 3.3 shows the boiling points of all potential components that exist during the process, in a descending order. The boiling points of glucose and LA are not presented in the table, because they decompose before evaporation can take place under atmospheric pressure.

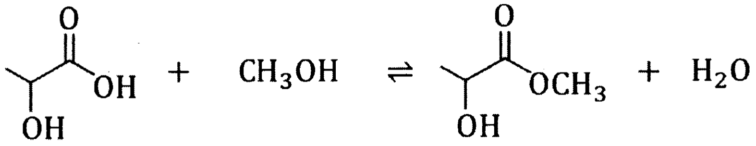


Figure 3-5: Esterification of lactic acid with methanol

Table 3.3: Boiling points of all compounds involved in the distillation process [C°]

Glucose	Lactic Acid	Butyric Acid	Methyl Lactate	Acetic Acid	Methyl Butyrate	Water	Methanol	Methyl Acetate
-	-	163.3	144.8	117.9	102.5	100	64.7	57.1

This reactive distillation column is followed by a simple separation column to remove glucose and other potential non-volatile acids, including unreacted butyric acid and LA. The outlet stream from the top of the column is sent to the second reactive distillation column, where methyl lactate is returned to LA through hydrolysis (the right-to-left reaction in the equation shown in Figure 3-5). At the same time, methanol and water are separated from the top, while 99% purity of LA is produced at the bottom of the column.

3.1.5 Methanol Recycling

Methanol, the key reactant in the esterification reaction and the by-product of the hydrolysis reaction, is recycled back to the first reactive distillation column. As methanol exiting the second reactive distillation column is diluted with water, another separation column is required to enhance the concentration of methanol before being recycled. Ideally, there would be no loss of methanol under the assumptions that the complete conversions take place for the two reactions and methanol is perfectly separated in distillation columns. However, in the process simulation conducted for this thesis, approximately 40% of methanol is lost when methanol is vaporized along with volatile products in the first reactive distillation column, while 16% of methanol disappears when methanol is removed along with water in the last separation column.

3.2 Simulation Results

The purification process from the evaporator to the methanol separator has been simulated using Aspen Plus, and process variables have been optimized to achieve a high LA purity of 99.9%. The process variables shown in Table 3-4 were varied to obtain the specified design specifications of each major piece of equipment - the reactive distillation column for esterification (RD:ESTER), the methyl lactate separator (GLU:SEP), and the reactive distillation column for hydrolysis (RD:HYDR).

For instance, sensitivity analyses were carried out for RD:ESTER by varying the number of stages, the distillate to feed ratio, and the reflux ratio, which were to determine the optimum values for limiting the mass fraction of methyl butyrate at

Table 3.4: Optimized process variables

No.	Equipment	Process variables	Design specifications	Optimized process variable value
1	Reactive distillation column for esterification (RD:ESTER)	No. of stages	Mass fraction of methyl butyrate in MELA+ (Target: 0.001)	10
2		Distillate to feed		0.89
3		Reflux ratio		0.7
4	Methyl lactate separator (GLU:SEP)	No. of stages	Mole recovery of methyl lactate from MELA+ to MELA++ (Target: 0.99)	15
5		Distillate to feed		0.99
6		Reflux ratio		1
7	Reactive distillation column for hydrolysis (RD:HYDR)	No. of stages	Mass purity/Mass flow of lactic acid in LA99+ (Target: 0.999/maximum)	10
8		Distillate to feed		0.93
9		Reflux ratio		0.95

the bottom stream of RD:ESTER to 0.001. As also pointed out by Bapat et al. in [4], the distillate to feed ratio had the most significant effect, while the two other variables did not produce a remarkable change in the mass fraction of methyl butyrate. Thus, the design specification function in Aspen Plus was used only for the distillate to feed ratio, in order to change the variable in a much smaller scale and determine the best possible value that can achieve the specific mass fraction. Similarly, the process variables of GLU:SEP were optimized to minimize the loss of methyl lactate from this separator. Lastly, for RD:HYDR, both the distillate to feed ratio and reflux ratio were varied using the design specification function, to obtain the maximum possible mass purity and mass flow of LA in the product stream (LA99+). The simulation results with these optimized process parameters are summarized in Table 3.5, which lists important stream results. Note that the equipment and stream names used are specified in the process flow diagram (Figure 3-2).

Table 3.5: Stream results table

Parameter/stream	FEED	METHFEED	LA-HEAT	MELA+	MELA++	METHANOL	LA99+
Temperature (C°)	25.0	25.0	101.0	107.5	119.6	74.9	213.9
Pressure (atm)	1	1	1	1	1	1	1
Mass flow (kg/hr)	3623.7	60.7	1066.1	259.0	250.1	42.1	144.1
Mass fraction (Mass purity)							
Lactic acid	0.043		0.145	0.018			0.999
Acetic acid	0.005		0.006				
Butyric acid	0.006		0.005	0.001			
Glucose	0.001		0.002	0.008			
Water	0.945	0.004	0.841	0.301	0.312	0.156	0.001
Methanol		0.996				0.844	
Methyl Lactate				0.670	0.687		
Methyl Acetate							
Methyl Butyrate				0.001	0.001		

Chapter 4

Economic Performance Assessment

4.1 Introduction

The ultimate objective of this thesis is to assess whether the waste-to-LA technology is technically and economically feasible to be implemented at a commercial scale. Once a process to manufacture polymer-grade LA is designed, cost estimation and profitability analysis need to be conducted before making an investment decision. In terms of the potential geographic location for implementing this technology, two different scenarios were examined: the U.S. and India. With reference to the standard engineering economic analysis procedures described in [54], the economic performance assessment was conducted as follows:

1. Develop baseline models to estimate Fixed Capital Investment (FCI), Total Capital Investment (TCI), and Total Product Cost (TPC) for a 50 tons/day capacity plant designed in Chapter 3.
2. Evaluate the economic profitability of this plant by developing a baseline model for Net Present Value (NPV), based on estimated TCI, TPC, and revenue.
3. Identify various sources of irreducible uncertainty in the baseline models for TCI, TPC, and NPV. Subsequently, conduct a Monte Carlo simulation to take into account the effect of irreducible uncertainties on the plant's economic performance.

4. Conduct comparative/sensitivity analyses to investigate how the capital and operating costs - as well as the overall profitability - are affected by various factors, such as the number of operators, the concentration of LA, and the required purity grade.

4.2 Total Capital Investment and Total Product Cost Baseline Estimation

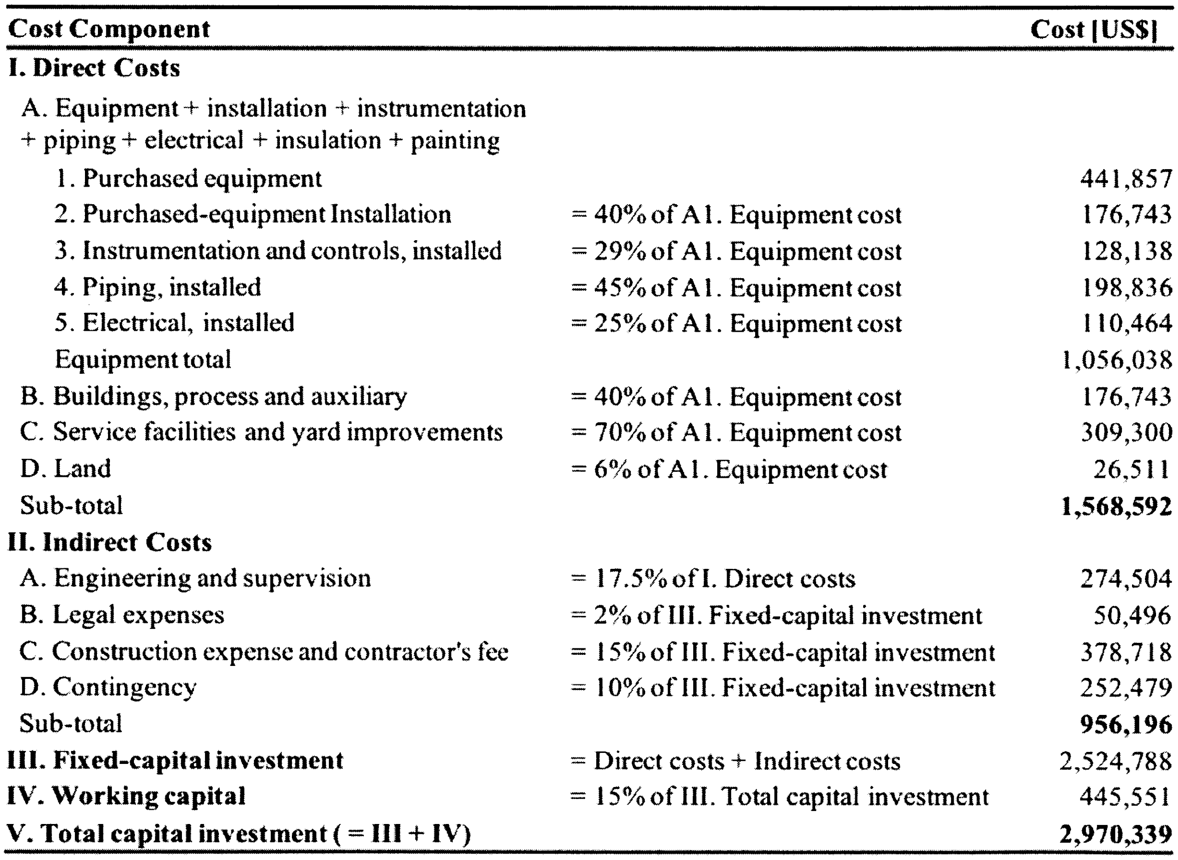
The scale-up and implementation of a chemical process requires a large sum of money, before the plant can actually be put into operation. TCI is the amount of capital initially needed prior to operation commencement, for various expenses such as purchasing and installing the necessary machinery and equipment, as well as obtaining land and service facilities, etc. In addition to capital investment, the estimation of annual costs incurred to operate a plant and sell products, i.e. TPC, is an essential part of the economic analysis. In contrast to TCI which occurs only in the beginning of a project, TPC is a recurring cost as long as the plant is in operation, and thus it has the power to alter cash flow and profitability of a project significantly. Following the conventional practice of engineering economic assessment described in [54], baseline models for TCI and TPC estimation were developed. A list of all cost components of TCI and TPC (model inputs) can be found in Table 4.1 and Table 4.3, which also present the baseline estimates corresponding to the expected values of all the uncertainty sources. The estimates shown in these tables are based on the U.S. data.

4.2.1 Total Capital Investment (TCI)

The TCI of a plant is defined as Equation 4.1, the sum of the fixed capital investment (FCI) and the working capital (WC).

$$\mathrm{TCI} = \mathrm{FCI} + \mathrm{WC} \tag{4.1}$$

Table 4.1: Estimation of total capital investment



Cost Component		**Cost [US$]**
I. Direct Costs		
A. Equipment + installation + instrumentation + piping + electrical + insulation + painting		
1. Purchased equipment		441,857
2. Purchased-equipment Installation	= 40% of A1. Equipment cost	176,743
3. Instrumentation and controls, installed	= 29% of A1. Equipment cost	128,138
4. Piping, installed	= 45% of A1. Equipment cost	198,836
5. Electrical, installed	= 25% of A1. Equipment cost	110,464
Equipment total		1,056,038
B. Buildings, process and auxiliary	= 40% of A1. Equipment cost	176,743
C. Service facilities and yard improvements	= 70% of A1. Equipment cost	309,300
D. Land	= 6% of A1. Equipment cost	26,511
Sub-total		**1,568,592**
II. Indirect Costs		
A. Engineering and supervision	= 17.5% of I. Direct costs	274,504
B. Legal expenses	= 2% of III. Fixed-capital investment	50,496
C. Construction expense and contractor's fee	= 15% of III. Fixed-capital investment	378,718
D. Contingency	= 10% of III. Fixed-capital investment	252,479
Sub-total		**956,196**
III. Fixed-capital investment	= Direct costs + Indirect costs	2,524,788
IV. Working capital	= 15% of III. Total capital investment	445,551
V. Total capital investment (= III + IV)		**2,970,339**

The FCI is the capital required to purchase and install the necessary tangible assets and provide the manufacturing and plant facilities needed for complete process operation. In addition, the WC represents the extra cash that the project needs to prepare to initiate and run the operation over a month, as the operation requires day-to-day expenses such as raw materials. Typically, it can be estimated to be about 15% of the TCI [54].

The FCI can be calculated by summing up all direct and indirect costs. As shown in Table 4.1, the most essential component of the direct costs is the equipment cost, which is used as a base in estimating all the other costs that are associated with purchasing the physical assets required to construct a plant. Equipment sizing and cost estimation were conducted based on the process simulation results as well as other references, as explained below. Besides the direct costs, the indirect costs also account for a significant proportion of the FCI, which include expenses for engineering and supervision, legal advice, contractors, and contingency.

Equipment Cost

The estimated costs of each piece of equipment and the methods used to derive these costs are shown in Table 4.2. Aspen Process Economic Analyzer was used to cost out all the equipment included in the Aspen process simulation, from the evaporator to the separation column for methanol recycling. The cost of the grinder was estimated using the following purchase cost equation for hammer mills, where W is the feed rate [ton/hr] [59]:

$$C_p = 3000W^{0.78} \tag{4.2}$$

Among different types of particle size reduction equipment, the equation for hammer mills was chosen because the range of feed rate was adequate for our processing needs, which is 100 tons/day, i.e. 4.17 tons/hr. Lastly, vendor quotations were used to estimate the costs of the remaining equipment, from the pump to the centrifuge. For the India case, the total equipment cost was adjusted using an investment site factor of 0.85 in order to take into account the difference in prices between the U.S.

Table 4.2: Estimation of equipment cost

	Equipment	Symbol	Cost [US$]	Source
1	Grinder	-	9,132	Equation
2	Pump	-	1,725	Vendor
3	Anaerobic Digester	-	25,000	Vendor
4	Filter Press	-	15,000	Vendor
5	Staging Tank	-	25,000	Vendor
6	Acidification Reactor	-	25,000	Vendor
7	Centrifuge	-	5,500	Vendor
8	Evaporator	EVAPOR	15,200	Aspen Process Economic Analyzer
9	Heat Exchanger	HEAT2	7,700	Aspen Process Economic Analyzer
10	Cooler	COOLER	10,800	Aspen Process Economic Analyzer
11	Reactive Distillation Column : Esterification	RD:ESTER	104,600	Aspen Process Economic Analyzer
12	Separation Column : Non-volatile impurities	GLU-SEP	59,400	Aspen Process Economic Analyzer
13	Reactive Distillation Column : Hydrolysis	RD:HYDR	106,800	Aspen Process Economic Analyzer
14	Separation Column : Methanol recycle	METH:REC	31,000	Aspen Process Economic Analyzer
	Total Equipment Cost		**441,857**	

and India [59].

4.2.2 Total Product Cost (TPC)

The TPC occurs annually and, in general, categorized into manufacturing costs and general expenses [54]. The former is further divided into fixed and variable operation and maintenance (O&M) costs. Fixed O&M costs are constant expenses and do not vary depending on production levels, while variable O&M costs change in proportion to the volume of production. Each of them is explained in more details in the following section.

Fixed O&M Costs

The components of fixed O&M costs include operating labor, direct supervisory and clerical labor, maintenance and repair, and insurance costs. For example, even if a project leader decides to cut down the production level of LA, salaries for plant operators and insurance still need to be paid and cannot be reduced. Based on heuristics [54], each cost component can be estimated as a certain percentage of the FCI. The costs of maintenance and repairs are roughly 4% of the FCI, while insurance accounts for 0.7% of the FCI.

Operators and staff are crucial to run the plant, and their annual wages account for a large fraction of the TPC. As with other cost components, the operating labor costs can be also estimated as a percentage of the FCI; nevertheless, available data and interviews with industry and local experts were used instead, for more accurate estimation and to take into account the difference between two geographical locations: the U.S. and India. The operation of this plant requires two types of personnel: 1) unskilled staff who segregate food waste to keep the high quality of feedstock, and 2) engineers who have a modest technical background to lead operation, maintenance and troubleshooting.

The number of unskilled staff members depends highly on the quality of food waste being supplied (more or less contaminated with non-food waste) as well as how

Table 4.3: Estimation of total product cost

Cost Component		Cost [US$]
I. Manufacturing costs		
A. Operating costs		
1. Fixed operation and maintenance (O&M) costs		
a. Operating labor cost		663,000
b. Direct supervisory and clerical labor cost	= 15% of Operating labor cost	99,450
c. Maintenance and repairs	= 4% of Fixed capital investment	100,992
d. Insurance	= 0.7% of Fixed capital investment	17,674
Fixed O&M costs total		881,115
2. Variable operation and maintenance (O&M) costs		
a. Raw materials		
Organic waste		-
Lime ($CaCO_3$)		53,900
Sulfuric acid (H_2SO_4)		51,736
Methanol (CH_4)		279,004
Water (H_2O)		1,221
Raw materials total		385,860
b. Utilities		513,998
c. Waste disposal		220,482
Variable O&M costs total		1,120,340
B. Plant overhead costs	= 10% of Total product cost	271,404
Manufacturing costs total		**2,272,859**
II. General expenses		
A. Administrative costs	= 3.5% of Total product cost	94,991
B. Marketing costs	= 4.0% of Total product cost	108,562
D. Financing interests	= 8.0% of Total capital investment	237,627
General expenses total		**441,180**
III. Total product cost (= I + II)		**2,714,039**

mechanized the secondary segregation and feeding process are. If the plant receives pure food waste or deploys conveyors or trommels, it requires fewer staff members, compared to when the plant needs to process mixed feedstock with an unmechanized segregation process. Based on interviews, the number of unskilled workers was set to 12 in the baseline model, assuming that the feedstock would be high-quality food waste and the plant would be somewhat mechanized. As this number is uncertain and has a large impact on the TPC estimate, the sensitivity analysis was conducted to investigate how it affects the economic performance of the plant, as illustrated in Section 5.3.2. Further, the number of skilled engineers required especially for the distillation process was assumed to be three for the capacity of 50 tons.

Moreover, the annual wage of each type of employee significantly varies across regions and countries. For the U.S. case, the baseline model referred to annual mean wages in Massachusetts, published in Bureau of Labor Statistics as of May 2016 [49]. While the annual mean wage of refuse and recycle material collectors was used for 1) unskilled staff, the corresponding number of chemical plant and system operators was used for 2) skilled engineers. Each ranges from 1) USD 31,110-49,040 and 2) USD 50,820-70,580. On the other hand, for India, we used data received from local and industry experts who have experience in operating biogas plants in India. Biogas plants are technologically similar, particularly the roles that require more laborers. The annual mean wages are significantly lower than those in the U.S., ranging from USD 2,400-3,600 for unskilled workers and USD 6,000-18,000 for engineers.

Variable O&M Costs

Variable O&M costs change in proportion to the production level of LA, which means the costs would be reduced to half when the plant cuts down its production level in half. These expenses include the costs of raw materials, utilities, and waste disposal. The amount and unit price of each raw material required for the process, such as organic waste, lime, sulfuric acid, methanol, and water, are described in Table 4.4. While the required volumes were derived from the mass balance results, several reliable price and market analysis reports, such as ICIS, were referred for the unit prices

[23, 59]. Methanol accounts for approximately 70% of the total costs of raw materials, which implies that the methanol recycling process is crucial to reduce the TPC.

Table 4.4: Estimation of raw material costs

Raw Materials	**Volume**		**Cost**			**Total Cost**
		MIN	**MAX**	**AVG**		**[$/year]**
a. Organic waste	50 tons/day	0	0	0	[$/ton]	-
b. Lime (CaCO3)	1 tons/day	130	178	154	[$/ton]	53,900
c. Sulfuric acid (H2SO4)	2.1 tons/day	50	94	72	[$/ton]	51,736
d. Methanol (CH4)	394.6 gal/day	1.51	2.53	2.02	[$/gal]	279,004
e. Water (H2O)	52.1 tons/day	0.067	0.067	0.067	[$/ton]	1,221

The utilities costs used for the economic analysis, including electricity, cooling water, and steam, are shown in Table 4.5, which is based on the data available in published literature [59]. Moreover, as described in the previous chapter, the process still leaves a certain amount of solid waste and gypsum. The treatment and disposal of the generated solid waste also need to be considered as a part of the production costs, which was also included in Table 4.5.

Table 4.5: Unit cost of utilities and waste disposal

Utilities & Waste Disposal	**Cost**	
a. Electricity	0.04	[$/kW-hr]
b. Cooling water	0.013	[$/m^3]
c. High pressure steam	12.1	[$/1,000 kg]
d. Medium pressure steam	8.8	[$/1,000 kg]
e. Low pressure steam	5.5	[$/1,000 kg]
f. Solid waste treatment	0.02	[$/lb]

4.3 Revenue

The main revenue sources of the plant are sales of LA (purity: 99%) and tipping fees, as illustrated in Table 4.6. In estimating the revenue, the volume of LA generated for sales was calculated based on the process simulation results, while the price range of LA, USD 1.58-1.87 per kg, was referred from ICIS as the conservative selling price [23].

Along with the final product, the other major revenue stream is expected to come from the feedstock. In the U.S., a charge, which is generally called a tipping fee, is applied when a given quantity of waste is disposed of at a waste processing facility, such as landfills. This fee widely varies across facilities and states, depending on applicable waste management regulations and the capacity of available lands. For example, the tipping fee can be as low as USD 5.00 per ton in Texas, while it can be as high as USD 142.01 per ton in Washington [24]. The baseline model applied the tipping fees in Massachusetts, ranging from USD 60 to USD 100 per ton. In the India case, it was assumed that there would be no revenue from tipping fees. Although some cities like Mumbai and Bangalore have started introducing tipping fees to reduce the financial burdens on private treatment operators [28], the system has not been fully established, and open dumping of municipal solid waste is still a common practice in many places in India. As the environmental concerns increase and the government tightens regulations in the future, we anticipate that revenue can be expected to rise due to added tipping fees.

Table 4.6: Estimation of total revenue

Revenue Sources	**Volume**	**Selling price**				**Revenue**
		MIN	**MAX**	**AVG**		**[$/year]**
Lactic acid (99%)	3456 kg/day	1.58	1.87	1.73	[$/kg]	2,093,370
Tipping Fee	50 tons/day	60	100	80	[$/ton]	1,400,000
	Total Revenue					**3,493,370**

4.4 Profitability Analysis: Net Present Value

The net present value (NPV) is one of the most widely used methods to evaluate an investment in an engineering project, representing the intrinsic value that will be added if the investment is undertaken. The decision rule is to accept the project if the NPV is positive and to reject the project if it has the negative NPV [10]. The baseline NPV is calculated as the difference between the gross present value (GPV) of future net cash flows and the TCI (Equation 4.3):

$$NPV = GPV - TCI \tag{4.3}$$

Further, as shown in Equation 4.4, the GPV is defined as the sum of the discounted cash flows over the lifetime of the plant, which was assumed to be 30 years in this assessment:

$$GPV = \sum_{t=1}^{30} \frac{CF_t}{(1+r)^t} = \frac{CF_1}{1+r} + \frac{CF_2}{(1+r)^2} + \ldots + \frac{CF_{30}}{(1+r)^{30}} \tag{4.4}$$

where CF_t is the nominal net cash flow in year t and r is the nominal discount rate. In this assessment, CF_t was calculated using Equation 4.5, by subtracting from the reportable net income (I_t) the combined federal and state tax in which the depreciation cost was also taken into account:

$$CF_t = I_t - (I_t - FCI \cdot D_t) \cdot (\Theta_{Federal} + \Theta_{State}) \tag{4.5}$$

In this equation, FCI is the fixed capital investment, D_t is the depreciation rate in year t, and $\Theta_{Federal}$ and Θ_{State} are the federal corporate tax rate and the state and local sales tax rate. First, the reportable net income (I_t) was estimated as the difference between the revenue generated in year t (R_t) and the total product cost incurred in year t (TPC_t) as shown in Equation 4.6:

$$I_t = R_t - TPC_t \tag{4.6}$$

Both R_t and TPC_t were adjusted for the inflation rate. In specific, the average inflation rates from 2010 to 2016 in the U.S. and India, respectively 1.63% and 8.32%, were assumed for the baseline analysis [47, 50]. Subsequently, the combined tax was calculated based on the net taxable income, which is I_t minus the depreciation cost $(FCI \cdot D_t)$. Depreciation is an annual income tax deduction allowed for a taxpayer, in order to recover the deterioration of long-term tangible assets, such as machinery, equipment, and buildings. For tax purposes, it is allowed to deduct the depreciation cost as a business expense from the net income. The IRS Modified Accelerated Cost Recovery System (MACRS) was followed to calculate the depreciation cost, assuming that the recovery period of assets is 20 years [26]. In addition, $\Theta_{Federal}$, which depends on the taxable income level, was defined by the federal corporate tax schedule from the Internal Revenue Service (IRS), U.S. Department of the Treasury [25], while the combined state and average local tax rate in Massachusetts as of 2015 was used as Θ_{State} [17]. In the case of India, both $\Theta_{Federal}$ and Θ_{State} were determined based on interviews from local experts. Finally, the assumptions used in the baseline model were summarized in Table 4.7, some of which were already described above.

Table 4.7: Assumptions in the NPV assessment

Baseline NPV Assumptions	Value	Unit
Plant Capacity	50	TPD
Plant Lifetime	30	years
Depreciation Period	20	years
Construction Period	1	year
Operating Days per Year	350	days
Cost Year of Analysis	2017	

4.5 Economic Performance Analysis under Uncertainty: Monte Carlo Simulation

The TCI, TPC, and NPV models illustrated in the previous sections involve inherent risks and uncertainties which are not irreducible. The sources of uncertainty are associated with contingent process operating conditions as well as an ever changing market and regulatory environment. The baseline assessment models adopt expected values for all the uncertain model inputs, which could lead to single-point and often unrealistic economic performance estimates [8, 57]. This was termed the "flaw of averages" by Savage, which states that estimations typically go wrong when a single average value is plugged into a model to represent an uncertain variable [58]. To overcome this problem and to better understand the impact of various uncertainties on the economic performance, a Monte Carlo simulation was carried out by using a range of values for each variable, instead of the single expected value. Monte Carlo techniques generate probability distributions of different outcomes in the presence of multiple uncertain parameters, as distinct from the conventional sensitivity analysis which varies only one input with the other variables fixed [57].

In this present study, Monte Carlo simulations were conducted using the software package R, based on the following methodological steps proposed by Ma, et al. [43]:

1. Develop the baseline models for the estimation of TCI, TPC, and NPV.
2. Identify the key uncertain inputs for each model.
3. Define the appropriate distribution profiles for each input.
4. Generate random values for all the identified uncertain variables from their own individual distributions. Repeat N times ($N=10^5$).
5. Perform the estimations of TCI, TPC, and NPV based on the developed models in Step 1. for all of the randomly generated values.
6. Generate the TCI/TPC/NPV distribution profiles from a broad range of outcomes derived in Step 5.

The identified sources of uncertainty are listed with their probability distributions in Table 4.8 and Table 4.9, respectively for the cases in the U.S. and India. For the majority of variables without any accumulated data from past experience, a simple uniform distribution (UD) was adopted, which is determined by the variable's minimum and maximum values with the constant probability within the range. In addition, when the most likely value of a parameter is available, the variable used a triangular distribution (TD), which has a triangle-shaped probability density function defined by the minimum, maximum and mode. Lastly, a bootstrap distribution (BD) was applied to a variable which has its historical data available, using re-sampling methods.

Table 4.8: Uncertain cost model inputs and corresponding probability distributions: the United States

Uncertainty driver	Distribution	Minimum	Maximum	Most Likely
Total Capital Investment (TCI)				
Ratio for purchased-equipment installation	UD	25.0%	55.0%	
Ratio for instrumentation and controls, installed	UD	8.0%	50.0%	
Ratio for piping, installed	UD	10.0%	80.0%	
Ratio for electrical, installed	UD	10.0%	40.0%	
Ratio for buildings, process and auxiliary	UD	10.0%	70.0%	
Ratio for service facilities and yard improvements	UD	40.0%	100.0%	
Ratio for land	UD	4.0%	8.0%	
Ratio for engineering and supervision	UD	5.0%	30.0%	
Ratio for legal expenses	UD	1.0%	3.0%	
Ratio for construction expense & contractor's fee	UD	10.0%	20.0%	
Ratio for contingency	UD	5.0%	15.0%	
Ratio for workin capital	UD	10.0%	20.0%	
Total Product Cost (TPC)				
Lime ($CaCO_3$) unit price [\$/ton]	UD	130	178	
Sulfuric Acid (H_2SO_4) unit price [\$/ton]	UD	50	94	
Methanol (CH_4) unit price [\$/gal]	UD	1.51	2.53	
Water (H_2O) unit price [\$/ton]	UD	0.067	0.067	
Annual wage of engineers [\$/year]	UD	50,820	70,580	
Annual wage of unskilled staffs [\$/year]	UD	31,110	49,040	
Ratio for maintenance and repairs	UD	2.0%	6.0%	
Ratio for insurance	UD	0.4%	1.0%	
Ratio for plant overhead costs	UD	5.0%	15.0%	
Ratio for administrative costs	UD	2.0%	5.0%	
Ratio for marketing costs	UD	2.0%	6.0%	
Ratio for financing interests	UD	6.0%	10.0%	
Net Present Value (NPV)				
Lactic acid selling price [\$/kg]	UD	1.58	1.87	
Tipping fee [\$/ton]	UD	60	100	
Inflation rate	RH	Historical data from 2010-2016, https://www.bls.gov/cpi/cpid1702.pdf		
State tax rate	TD	0%	9.45%	6.25%
Discount rate	UD	14.4%	16.00%	

Table 4.9: Uncertain cost model inputs and corresponding probability distributions: India

Uncertainty driver	Distribution	Minimum	Maximum	Most Likely
Total Capital Investment (TCI)				
Ratio for purchased-equipment installation	UD	25.0%	55.0%	
Ratio for instrumentation and controls, installed	UD	8.0%	50.0%	
Ratio for piping, installed	UD	10.0%	80.0%	
Ratio for electrical, installed	UD	10.0%	40.0%	
Ratio for buildings, process and auxiliary	UD	10.0%	70.0%	
Ratio for service facilities and yard improvements	UD	40.0%	100.0%	
Ratio for land	UD	4.0%	8.0%	
Ratio for engineering and supervision	UD	5.0%	30.0%	
Ratio for legal expenses	UD	1.0%	3.0%	
Ratio for construction expense & contractor's fee	UD	10.0%	20.0%	
Ratio for contingency	UD	5.0%	15.0%	
Ratio for workin capital	UD	10.0%	20.0%	
Total Product Cost (TPC)				
Lime ($CaCO_3$) unit price [$/ton]	UD	130	178	
Sulfuric Acid (H_2SO_4) unit price [$/ton]	UD	50	94	
Methanol (CH_4) unit price [$/gal]	UD	1.51	2.53	
Water (H_2O) unit price [$/ton]	UD	0.067	0.067	
Annual wage of engineers [$/year]	UD	6,000	18,000	
Annual wage of unskilled staffs [$/year]	UD	2,400	3,600	
Ratio for maintenance and repairs	UD	2.0%	6.0%	
Ratio for insurance	UD	0.4%	1.0%	
Ratio for plant overhead costs	UD	5.0%	15.0%	
Ratio for administrative costs	UD	2.0%	5.0%	
Ratio for marketing costs	UD	2.0%	6.0%	
Ratio for financing interests	UD	6.0%	10.0%	
Net Present Value (NPV)				
Lactic acid selling price [$/lb]	UD	1.58	1.87	
Tipping fee [$/ton]	UD	-	-	
Inflation rate	RH	Historical data from 2010-2016, OECD data		
State tax rate	TD	0%	9.45%	6.25%
Discount rate	UD	14.4%	16.00%	

Chapter 5

Results

5.1 Introduction

The results of the economic performance analysis are presented in this section. Section 5.2 shows the capital and operating expenses required to implement the proposed waste-to-LA process, respectively in the U.S. and India. In addition, the net present values (NPVs) for each case were presented in Section 5.3, along with the impact of discount rate changes on the profitability assessment results. Using the developed models, several sensitivity analyses were conducted to answer critical questions in making the investment decision on whether to scale up this technology, which was described in Section 5.4.

5.2 Capital and Operating Expenses for Production

The cumulative probability functions of fixed capital investment (FCI), total capital investment (TCI), and total product cost (TPC) for the proposed waste-to-LA plant were generated from the cost analysis illustrated in Chapter 4. Two different scenarios were considered in terms of the location where this scale-up project takes place: one in the U.S. and the other in India. The FCI/TCI cumulative probability distribution profiles for each scenario are shown, respectively in Fig 5-1 and Fig 5-2, while the results of TPC for both cases are shown comparatively in Fig 5-3. As opposed to single-point estimates, the following information valuable for the investment decision can be easily obtained from the distribution profiles:

- The expected values of the FCI, TCI, TPC, which are presented with gray/black dot lines, can be readily inferred from the graphs, which also visualize the possible ranges that each estimate could take. While the mean values of FCI and TCI were estimated to be respectively USD 2.53 million and USD 2.98 million in the U.S. case (see Figure 5-1), the estimates of the corresponding values were USD 2.15 million and USD 2.53 million in the Indian case (see Figure 5-2). Further, as shown in Figure 5-3, the means of TPC in both cases are respectively USD 2.68 million and USD 1.79 million. For all the costs, it is not only that the expected values are larger but also their ranges are broader in the U.S. case, compared to the case of India.

- Another important factor in making an investment decision is whether the estimated FCI/TCI/TPC would be lower than the investor's anticipated budgets. The aforementioned figures also show the probability that each cost falls below a certain target level. For example, if the target TCI level for this project is USD 3.5 million, the probability that it will be achieved is approximately 87.5% in the U.S. and 99.0% in India. Further, it can be readily deduced from Figure 5-3 that it is unlikely for the TPC to exceed the expected revenue in both cases.

- Conversely, the distribution profiles also inform a threshold value which the FCI/TCI/TPC does not go beyond with a certain percentage of possibility. For instance, in the U.S. case, it is estimated that the TCI and TPC will not go above USD 3.57 million and USD2.91 million with a probability of 90%. On the other hand, it is expected that the plant implemented in India will require less than USD 3.03 million for the TCI and annually incur less than USD1.94 million for the TPC, with a probability of 90%.

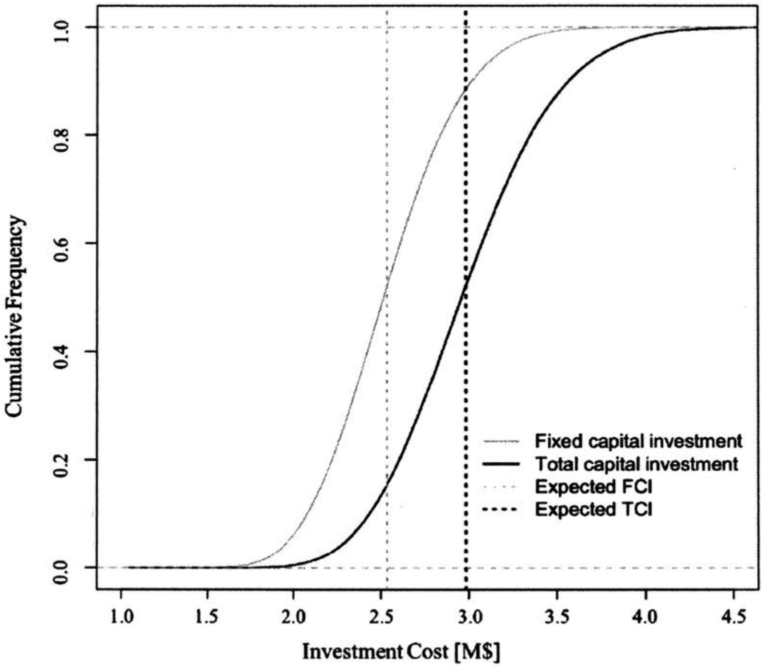


Figure 5-1: Capital investment distribution of a waste-to-LA plant based in the United States

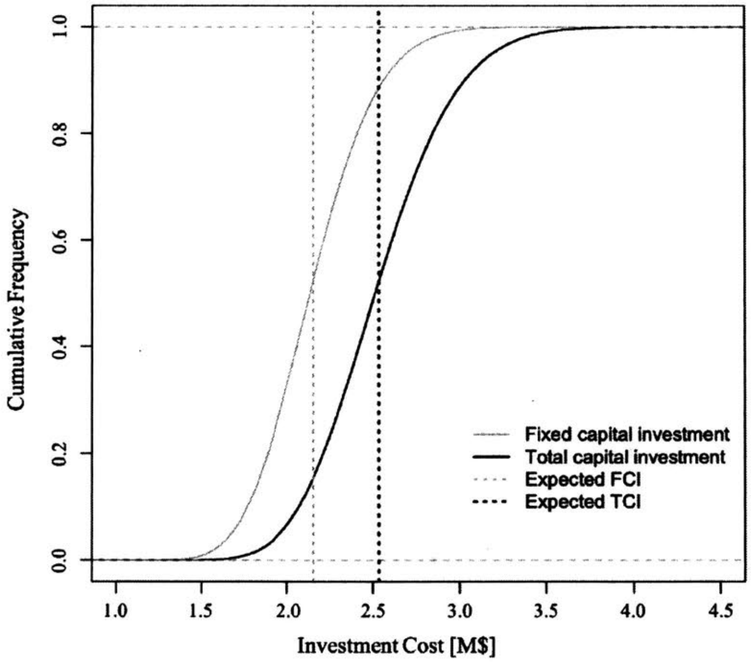


Figure 5-2: Capital investment distribution of a waste-to-LA plant based in India

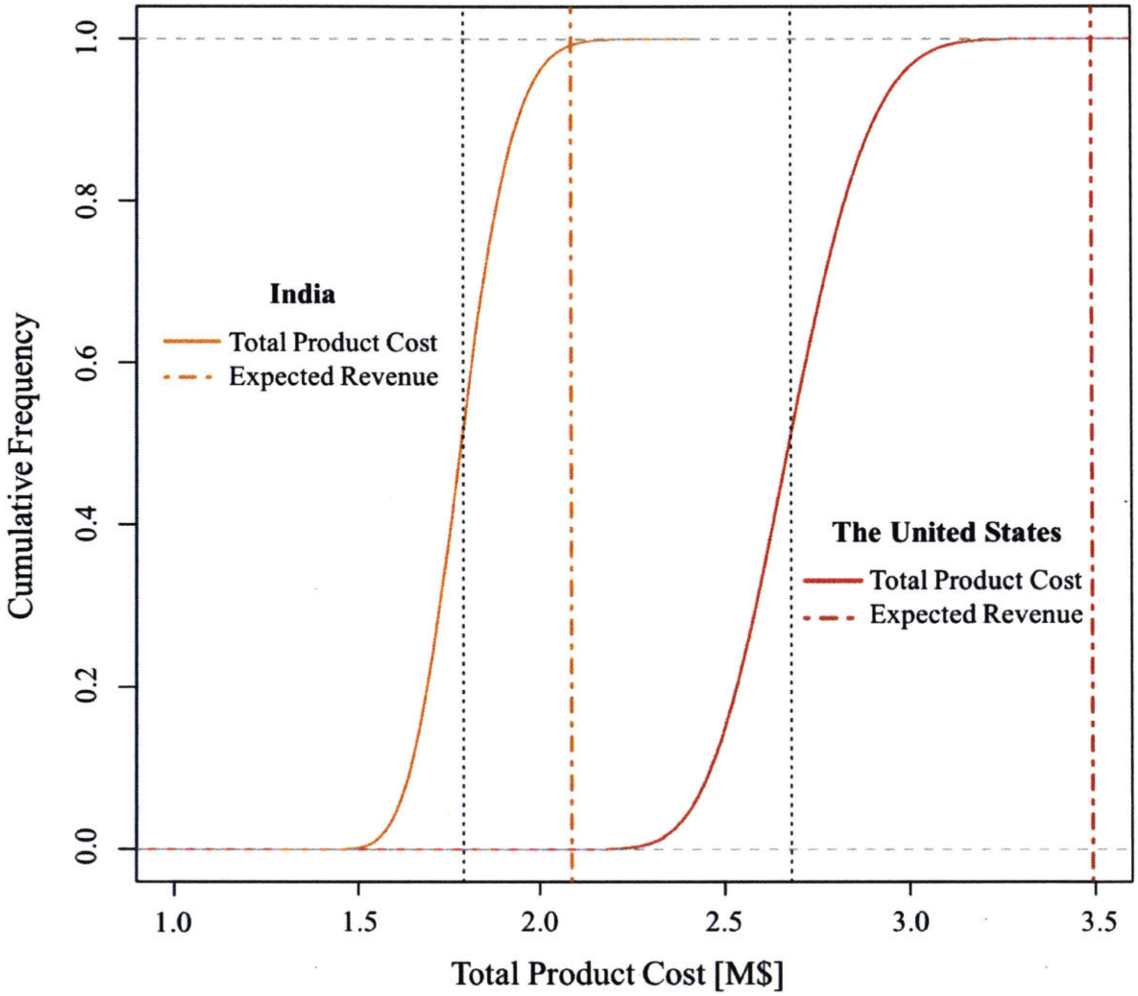


Figure 5-3: Total product cost distributions of a waste-to-LA plant: the United States and India

5.3 Profitability Analysis: NPV

The net present value (NPV) analysis was conducted to evaluate whether the proposed process has the potential to generate profits. Figure 5-4 shows the NPV cumulative distribution profiles generated from the baseline simulation results, respectively for the case of the U.S. and India. Further, this section also includes the results of sensitivity analyses to investigate how the NPV changes in response to changes in the number of unskilled workers as well as the discount rate. The methods used for the NPV analysis and Monte Carlo simulation are described in Section 4.4 and 4.5.

5.3.1 Baseline Results

The baseline models assumed the number of required skilled engineers as three and the number of unskilled staff as 12. Additionally, the nominal discount rate was assumed to be 12%. The other assumptions made in the base models are reported in Section 4.4. Based on the results of TCI, TPC, and revenue, the NPV was estimated, and the distribution profiles are shown in Figure 5-4. The expected value of the NPV is USD 1.95 million when the plant is implemented in the U.S., which is higher than the corresponding value in the case of India, USD 1.31 million. The probability that the NPV will be above zero is approximately 87.5% and 73.7% in the U.S. and India respectively, which indicates that there is a higher risk in India regardless of the cheaper capital and operating expenses. This is mainly because of the lack of a landfill tipping fee as a revenue source in India. It implies that the profitability can be significantly improved if landfill tipping fees become more common.

5.3.2 Operating Labor Costs

The operating labor costs account for the greatest proportion of the TPC in the case of the U.S., around a quarter of the total operating expenses, due to the high average annual wage. Further, as described in the previous chapter, the number of unskilled operators whose main responsibilities are to segregate food waste can vary depending on the quality of received feedstock and how automated the segregation process is.

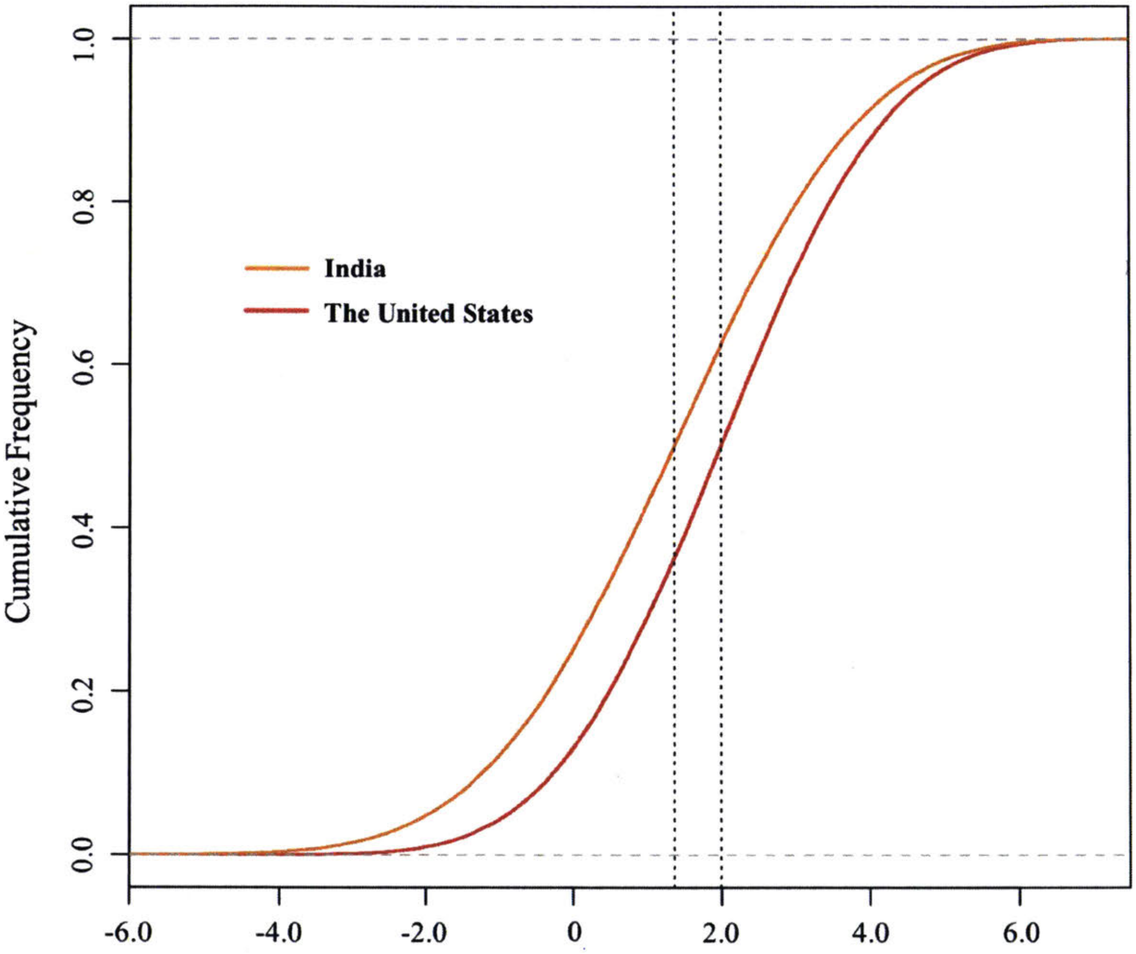


Figure 5-4: The baseline cumulative distributions of NPV: the United States and India

According to an industry expert, the plant without any automated segregation process may need over 20 staff members on hand when it receives a low quality of food waste (e.g. mixed with other waste). Thus, an sensitivity analysis was conducted to investigate how the NPV is impacted when the number of unskilled operators increase from 12. The results are shown in Figure 5-5 and Figure 5-6, respectively for the U.S. and Indian cases.

As it was presumed, the NPV distribution profiles significantly shifted to the left with the increasing number of unskilled operators in the case of the U.S. The expected values of the NPV are USD 0.93 million and USD 0.04 million for 15 and 18 operators; nevertheless, the value drops below zero when the number increases to 21. In contrast, in the case of India where the average annual wage is much lower, there was only a slight shift to the left, as demonstrated in Fugure 5-6. Even if the plant requires 24 unskilled staff members, the NPV still stays positive, approximately USD 0.74 million. These results indicate that the quality of feedstock is a crucial factor that needs to be considered to make the process profitable especially in the U.S., with less of an impact on an Indian plant.

5.3.3 Discount Rate

Future cash flows were discounted at the discount rate to reflect the time value of money (TVM) in the NPV analysis, according to Equation 4.4 in Section 4.4. The TVM is one of the core concepts in finance, which suggests that currently available money is more valuable than the same amount of money in the future due to alternative investment opportunities [42]. Thus, the discount rate can be understood as the opportunity cost of capital, or the interest rate that an alternative investment could potentially bring. There are two essential factors that the discount rate depends on: (1) the market's perceived level of risk associated with the project, and (2) how the project is financed [6, 8, 43]. With the same financing mechanism, the riskier the project is perceived, the larger the discount rate has to be used. In particular, a higher value is used when the project's environment is unstable, in terms of macroeconomics, operation, financing, and market. Assuming 100% equity financing, the

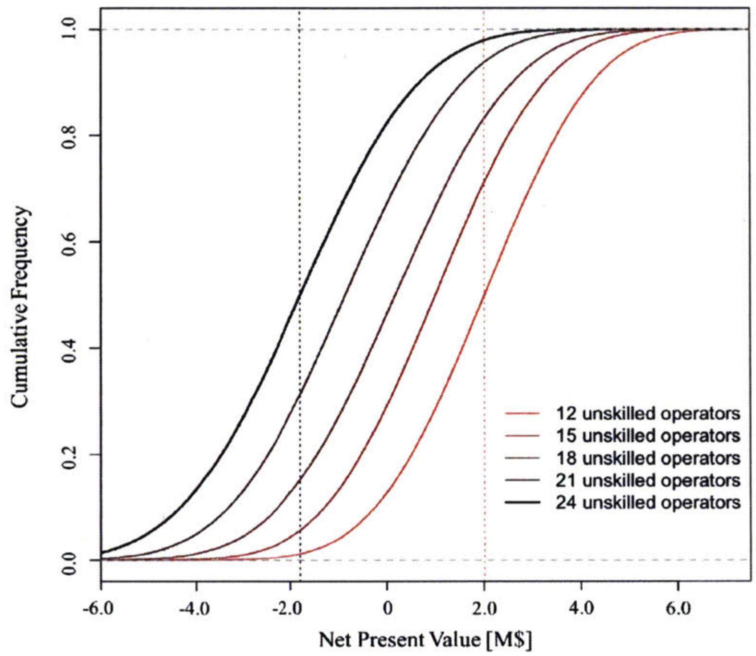


Figure 5-5: NPV cumulative distributions under various number of unskilled operators: the United States

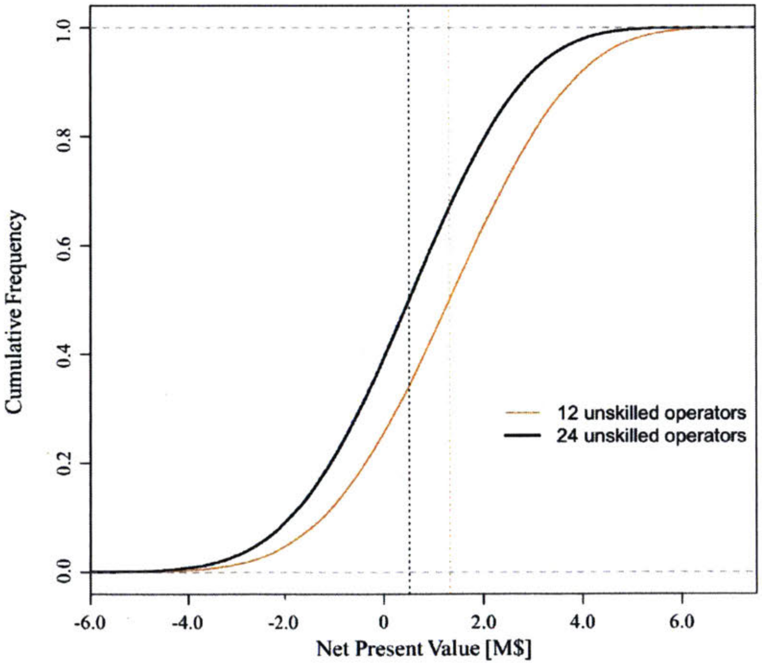


Figure 5-6: NPV cumulative distributions under various number of unskilled operators: India

discount rate is conventionally estimated as the sum of a risk premium associated with the specific project and the risk-free rate of return [6, 8, 43]. Nevertheless, it is not a straightforward task to estimate the risk premium applicable to the project under consideration.

In the NPV baseline models, the discount rate was assumed to be 12%, referring to the previous body of literature on the economic analysis of similar processes such as biogas production/anaerobic digestion [18, 33]. Nevertheless, a suitable discount rate is difficult to determine and is a significant uncertain part of the NPV estimation. To investigate how the NPV changes with a different discount rate, a sensitivity analysis was carried out within a reasonable range, by varying the discount rate from 6% to 20%. As illustrated in Figure 5-7, a higher discount rate not only drives down the expected NPV, but also reduces the probability that the NPV will be higher than a certain level while increasing the downside risk. Therefore, under the situation where the project-specific risks cannot be easily eliminated, it is important to strengthen the financing mechanism, in order to minimize the level of risk and increase the probability that the project is profitable.

5.4 Comparative Analysis of Economic Performance

The assessment conducted above was under the assumptions that 1) the performance of the developed technology will be constant, and 2) the process will generate LA of a certain targeted purity. However, the improvement of the technology in the future may significantly enhance the economic performance of the process, while undesirable conditions may deteriorate the technology performance proven on a bench scale and negatively affect the profitability. In addition, even though the analysis set the purity of final product as 99%, there are demands for other grades or even different products that could be manufactured using the same or similar technology. It is expected that the production of each grade or product results in different TCI, TPC, and NPV. This section illustrates the sensitivity analyses carried out to investigate how these variables change the economic performance. Further, based on the results

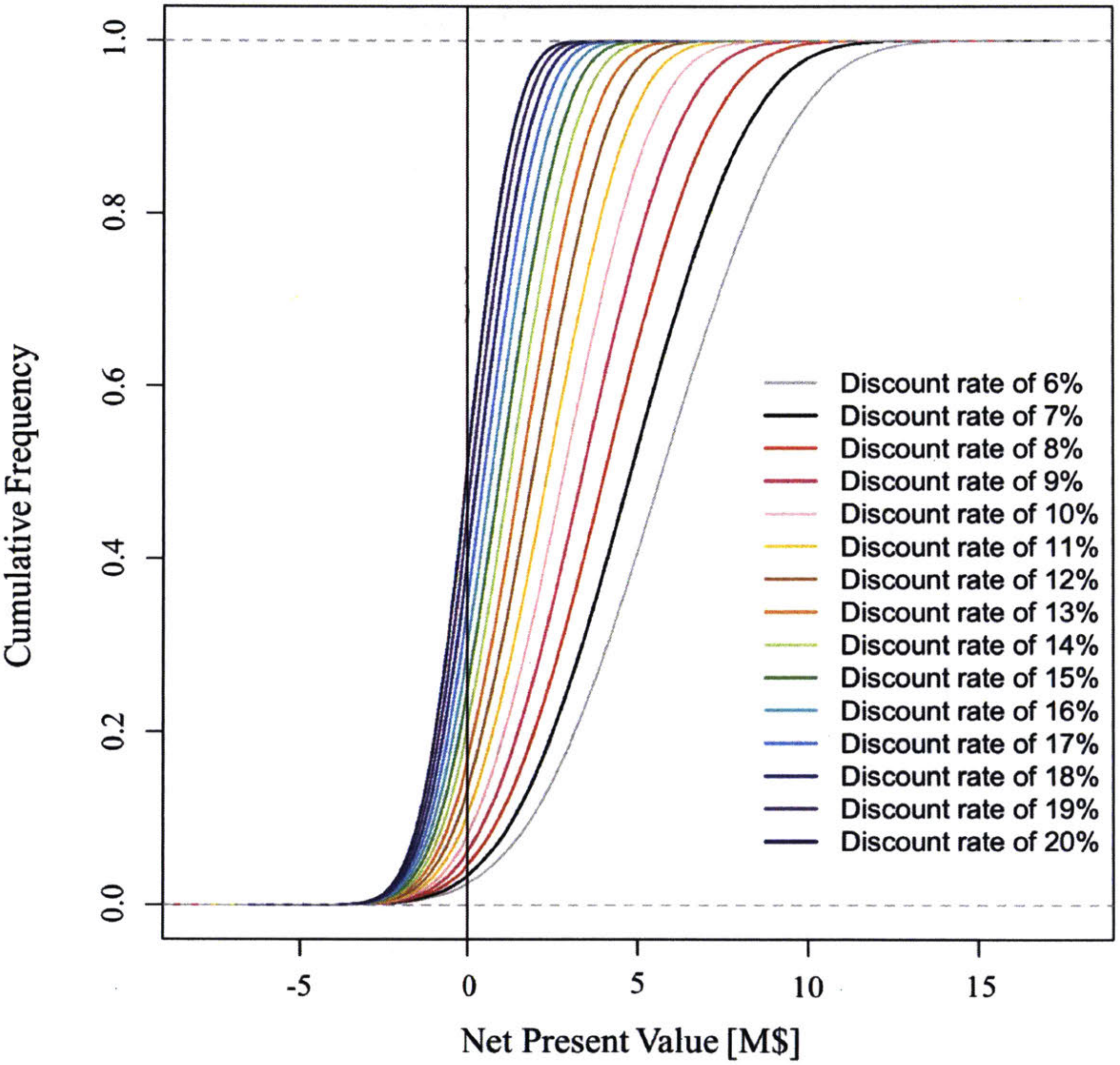


Figure 5-7: NPV cumulative distributions under various discount rates

and insights gained from the analysis, a Technology Commercialization Assessment Matrix (TCAM) was proposed with the aim of providing a framework based on which potential investors or technology developers can assess the economic performance of new technologies and make investment strategies for the commercialization.

5.4.1 Technology Performance

In the assessment described above, the concentration of LA generated through anaerobic digestion was assumed to be 44 g/L, which is a conservative number taken from experimental results. However, continuous efforts have been, and will be, made in the lab to enhance the technology's performance, that is to increase the concentration of LA produced. Simultaneously, there is a risk that the scaled-up anaerobic digester may not be able to achieve the same concentration of LA as the bench-scale bioreactor. To investigate how both scenarios could affect the economic performance of the plant, a sensitivity analysis was conducted by varying the LA concentration from 30 g/L to 80 g/L. The hypothesis was made that a higher concentration would reduce the utility cost associated with the evaporator (EVAPOR), because a less volume of water needs to be evaporated. It also might result in the decrease of TPC, as EVAPOR was considered as one of the most energy-intensive equipment.

Figure 5-8 shows the total utility cost per hour, and utility costs associated with the evaporator (EVAPOR) as well as the reactive distillation column for esterification (RD:ESTER). As it was hypothesized, the evaporator consumes less energy as the concentration goes up, according to the results from Aspen process simulations. However, it was also found that the total utility cost per hour increased from USD 59 to USD 69, when the concentration changes from 30 g/L to 80 g/L. The main contributor to the increase of total utility cost was found to be RD:ESTER, which needs to process a larger volume as the concentration of LA increases. Although the total utility cost increases with improved technology performance, it also enhances the volume of final product, as shown in Figure 5-9. To investigate how these changes affect the overall economic performance, the expected values of TCI, TPC, revenue, and NPV for each LA concentration (30, 44, 50, 60, 70, 80 [g/L]) were approximately estimated. As illustrated in Figure 5-10, it was found that the overall profitability (NPV) can be significantly improved by upgraded technology performance, because the revenue increase from LA is expected to be much higher than the increase in capital and operating expenses (TCI, TPC).

5.4.2 Targeted Applications of Final Product

The process design and economic assessment were conducted above, under the assumption that the technology developed at MIT would be commercialized for producing high-quality LA (99% purity), due to its high market growth potential. However, as the separation and purification of crude LA need to be integrated for producing the targeted final product, this application requires high capital and operating expenses, which results in higher investment risk. Additionally, in contrast to established technologies, lab-scale technologies are associated with even higher risk, as experimental results may not necessarily be replicated when they are scaled up. In order to lower the investment barriers, it is important to consider other potential applications of the technology as an intermediate step for a proof of scale. If another application can be achieved with lower capital costs, an initial investment can be made for this application and move towards more profitable projects, once the technology feasibility is proven in an industrial scale. In this study, two more applications, 1) food and beverage and 2) animal feed, were approximately evaluated using the economic assessment model described in Chapter 4, under the assumption that a plant will be operated in India. Table 5.1 shows the expected value of TCI, TPC, revenue, and NPV for each option, including the originally targeted market, i.e. poly-lactic acid (PLA).

Food and Beverage

LA has a variety of applications besides the industrial application as a monomer of PLA, as described in Section 2.3. According to the market analysis conducted by Feedback Consulting, the share of food and beverage in Indian LA and PLA industry

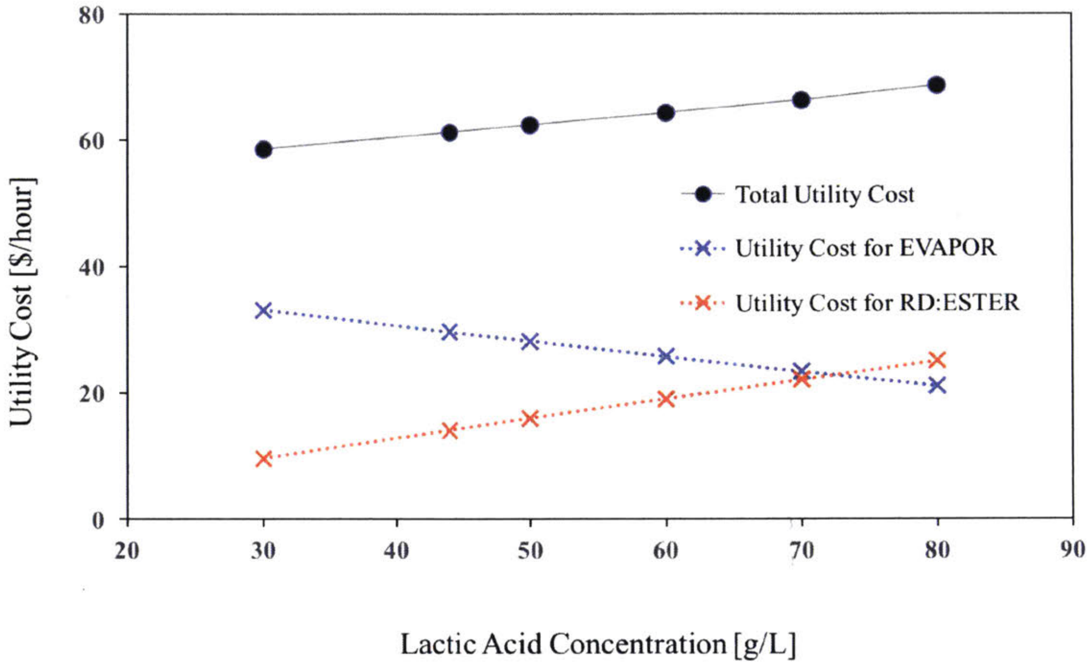


Figure 5-8: Estimated utility costs per hour under various LA concentrations

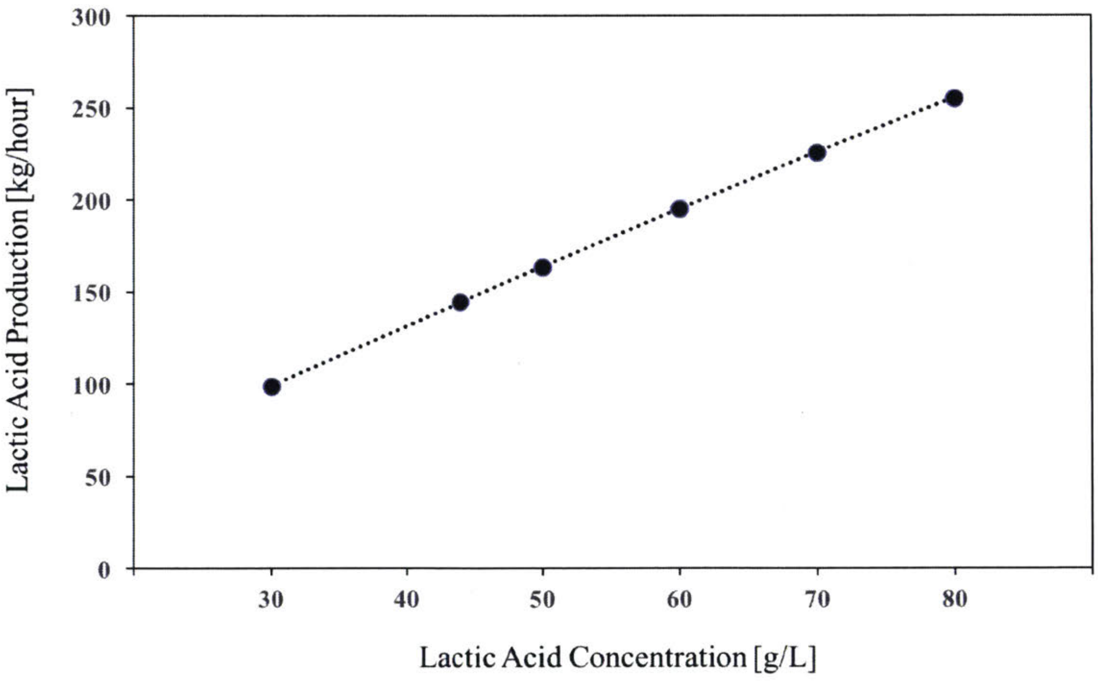


Figure 5-9: Estimated volumes of LA under various LA concentrations

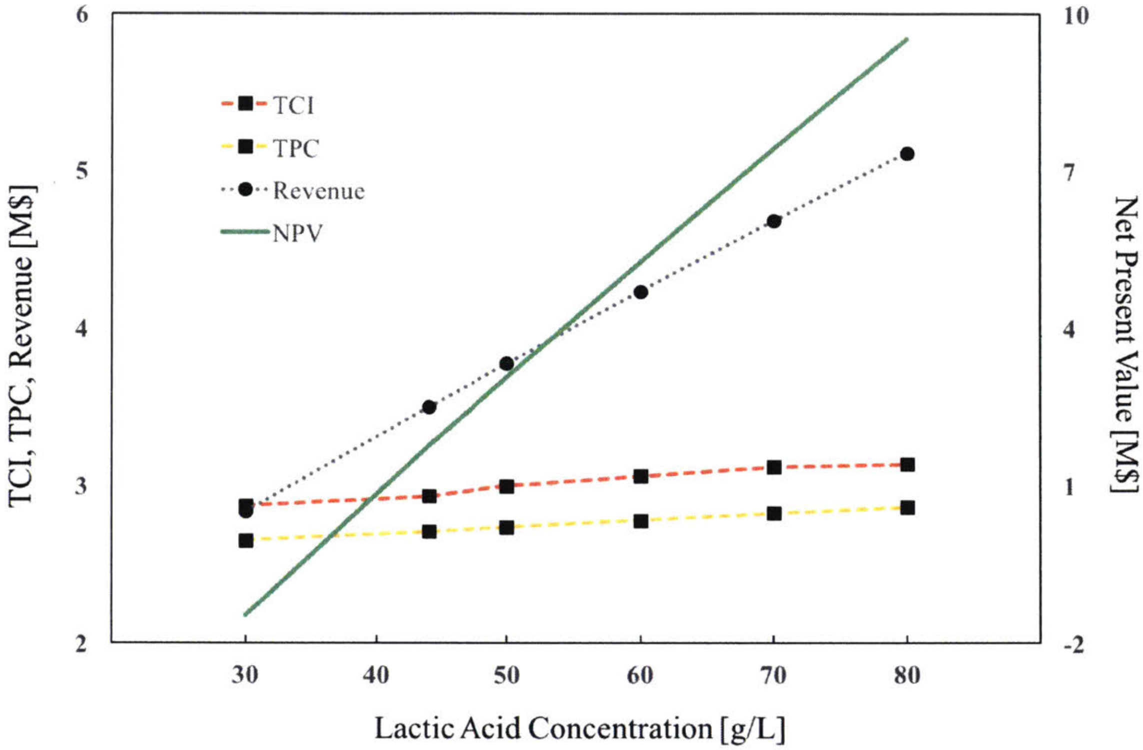


Figure 5-10: Expected TCI, TPC, revenue, and NPV under various LA concentrations

is currently the largest by value, accounting for about 32% as of 2015 [13]. Since the purity required for this segment is approximately 80% and the selling price of LA is expected to be lower, it was assumed that both TPC and revenue would be reduced comparing to the 99% LA production. For this analysis, the Aspen simulation model for the separation and purification process was adjusted to produce 80% LA, where it was found that the equipment cost and utility costs are reduced with lower purity of LA. As a supplemental study, a sensitivity analysis was conducted to investigate how the utility cost required for the separation and purification changes depending on the targeted purity (70, 80, 90, 99.9%), as shown in Figure 5-11. Further, the selling price of food-grade LA (80% purity) was assumed to be in the range of USD 1.0-1.1 per kg according to vendor quotations, while the hourly LA production was assumed to be 180.5 kg/hour based on the simulation results. As shown in Table 5.1, it is expected that the reduction in the expected revenue is not fully compensated by the decrease in the expected TCI and TPC. Further, the revenue is expected to be lower than the TPC, which results in a substantial drop in NPV. However, it has to be noted that the separation and purification technologies and process design were originally selected and optimized to achieve 99% purity. It is most likely that the process could be redesigned and further optimized to reduce the TCI and TPC for the production of 80% LA. Additionally, there are some factors that were not taken into account in this comparative analysis but may positively affect the NPV in more favorable conditions, such as the improvement of technology performance and the quality of feedstock.

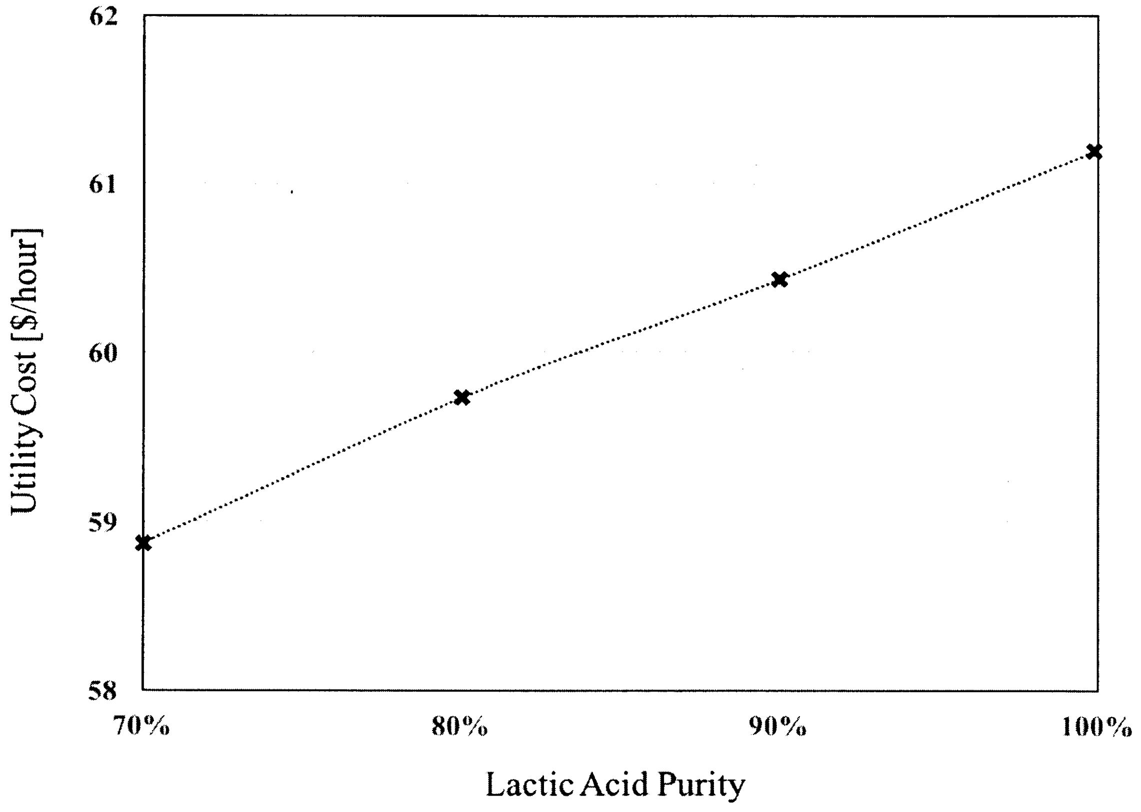


Figure 5-11: Total utility costs required for the production of LA with different targeted purities

Animal Feed

The separation and purification process accounts for the largest share of the total capital and operating expenses, as stated previously. An alternative hypothesis is that, if one did not have to separate and purify the LA, both TCI and TPC might decrease considerably, which would make the initial scale-up project more feasible. The same technology developed at MIT can be also applied to produce animal feed, by adding an additional fermentation reactor using *Yarrowia*. This aerobic *Yarrowia* reactor further converts LA and other acids into high-value animal feed. The overall process diagram is illustrated in Figure 5-12.

The following assumptions were made in estimating the approximate expected values of TCI, TPC, revenue and NPV. First, the same amount of feedstock (i.e. 50 tons of food waste mixed with the same volume of water) was assumed, while a conservative conversion rate, 0.21 [g of animal feed/g of LA], was used to calculate how much animal feed is produced from a certain amount of LA, based on experimental results. Subsequently, the quantity of animal feed generated from this process was estimated to be 791.74 kg per day. According to vendor quotations, the selling price of animal feed was assumed to be within the range of USD 400-1,000 per ton. Moreover, this analysis assumed that only one filter press is purchased and used for two different purposes, one to separate solid waste after the anaerobic digester and the other to remove the liquid from the cell mass, i.e. animal feed, generated from the *Yarrowia* reactor. In addition, the disposal fee of solid waste was assumed to be zero to be conservative, even though the solid waste could be sold as compost in the market. This is based on an interview with both local and industry wide experts who have had experience in the business of biogas production. Lastly, since this process is rather simple and does not involve a series of distillation columns, the number of skilled engineers required to operate and maintain the plant was assumed to be one, as opposed to three. On the other hand, the number of unskilled staff members who segregate food was presumed to be the same, as the same amount of food waste needs to be processed.

As shown in Table 5.1, the approximate expected values of TCI and TPC were estimated to be USD 0.43 M and USD 0.13 M, which are much lower than the other applications considered in this study. Further, the estimate of the expected revenue was USD 0.19 M, leading to a positive NPV (USD 0.32 M).

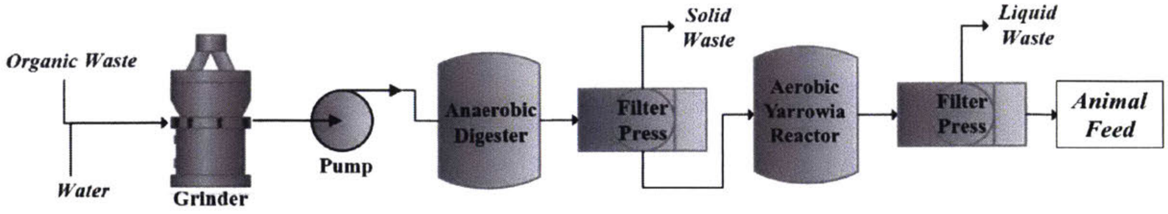


Figure 5-12: A proposed process diagram for the production of animal feed

Table 5.1: Comparative economic performance among three available applications

Targeted Application	**Animal Feed**	**Food/Beverage**	**Poly Lactic Acid**
Total Capital Investment (TCI)	USD 0.43 M	USD 2.46 M	USD 2.52 M
Total Product Cost (TPC)	USD 0.13 M	USD 1.76 M	USD 1.78 M
Revenue	USD 0.19 M	USD 1.54 M	USD 2.09 M
Net Present Value (NPV)	USD 0.32 M	USD - 4.19 M	USD 1.31 M
Additional Required Processes	Yarrowia Fermentation	Separation & Purification [Targeted Purity: 80%]	Separation & Purification [Targeted Purity: 99%]

5.4.3 Technology Commercialization Assessment Matrix

Table 5.1 provides the overall picture of commercialization potential for the novel microbial technology developed at MIT. It presents important factors to consider when making investment decisions, such as capital and operating costs and profitability, for each major application. As can be inferred from the table, the industrial application for the production of PLA is most likely to bring the largest profits, among the other applications. However, it also requires the highest capital and operating expenses, which significantly raises a barrier to funding or investment. This high risk could be mitigated by proving the lab-scale technology at industrial scale with small capital investment. As described in the previous section, the application to produce animal feed could be achieved with much smaller capital and operating expenses, as the process does not require the separation and purification units. Simultaneously, the animal feed production is expected to bring positive profits, although the profit scale is smaller than the polymer-grade LA production. Therefore, it could be proposed that, initially, the technology should be scaled up to produce animal feed, not only for profit purposes, but also with the main aim of proving whether the technology behaves as expected. Subsequently, once the technology is proven at scale, more capital can be injected into the plant to incorporate the separation and purification units and ultimately manufacture polymer-grade LA. For the production of food/beverage grade LA (80%), the negative NPV suggests that further research needs to be done to investigate whether there are other directions that could be taken to improve the economic performance. For example, one option is to further explore separation and purification processes that are better suited to the production of LA with 80% purity, as the process used in this analysis was selected and optimized for 99%. Another way is to explore other applications which have higher selling prices with the same purity requirement. Otherwise, an investment decision could be made to skip this application and target polymer-grade LA once the technology is proven at scale and sufficient capital is created from the production of animal feed.

This matrix (Table 5.1) can be used not only for this specific technology but also for other technologies with commercialization potential. A generalized form of this matrix is shown in Table 5.2, which is proposed as a Technology Commercialization Assessment Matrix (TCAM) in this thesis. The TCAM can be used as a framework for assessing the economical feasibility of a technology with multiple applications and making investment strategies for its commercialization. First, major markets/applications of a specific technology should be listed out with their required technology performances and market sizes. In general, the performance of a newly developed technology often determines the market/application for which the technology is commercialized. For example, when a novel material is developed, different markets/applications are targeted depending on the achieved durability and strength of a material. In the case of this project, the purity of LA corresponds to the technology performance. Further, for each market/application, its capital and operating expenses as well as its profitability should be estimated and compared, either approximately or in detail.

The comparison of these factors provides insights to make investment decisions as well as to determine the direction of technology development. Supposing that a technology has been proven to achieve all the listed performances, the matrix can be used to identify an investment strategy, not only in terms of the commercialization feasibility at present but also considering time as a dimension. For example, in the long term, one market/application, i.e. animal feed, can be the target of an initial investment as well as an intermediate step before moving toward the ultimate goal, i.e. polymer-grade LA, as suggested above. On the other hand, there are cases where technological progress still needs to be made in order to achieve a specific level of performance and be commercialized in the corresponding market. The TCAM also helps to determine whether the technology is worth further investment for performance enhancement, which could direct limited research funding into appropriate technologies from the perspective of commercialization. Lastly, as included in Table 5.2, there are other important factors that were out of the scope of this study but preferably should be taken into account in making decisions on investment and technology development. These factors include environmental impact and social value, which are increasingly used by venture capital as an important indicator in the evaluation of investment. Recently, more and more governments also place emphasis on these factors in deciding projects to support.

Table 5.2: Technology Commercialization Assessment Matrix (TCAM)

Technology Performance	**Low** **(-)**	**Medium** **(80%)**	**High** **(99%)**
Targeted Application	(Animal Feed)	(Food/Beverage)	(Poly Lactic Acid)
Capital Expenses (TCI)	(USD 0.43 M)	(USD 2.46 M)	(USD 2.52 M)
Operating Expenses (TPC)	(USD 0.13 M)	(USD 1.76 M)	(USD 1.78 M)
Revenue	(USD 0.19 M)	(USD 1.54 M)	(USD 2.09 M)
Profitability (NPV)	(USD 0.32 M)	(USD – 4.19 M)	(USD 1.31 M)
Environmental Impact	-	-	-
Social Value	-	-	-
Other Technologies Required	(Yarrowia Fermentation)	(Separation & Purification) [Targeted Purity: 80%]	(Separation & Purification) [Targeted Purity: 99%]
Associated Risk	-	-	-

Chapter 6

Concluding Remarks and Future Work

6.1 Summary

Innovative technology solutions are increasingly vital for tackling today's global challenges of resource exhaustion and unsustainable waste generation. As a novel approach to waste treatment, the laboratory of Professor Gregory Stephanopoulos at MIT has developed a sustainable process for lactic acid (LA) production based on anaerobic digestion of organic fraction of municipal solid waste (MSW). This lab-scale technology has great potential to serve as a cutting-edge solution to divert waste from landfills as well as to generate value from a renewable source with zero to negative costs. Among various applications, a particular focus was placed on poly-lactic acid (PLA), a biodegradable polymer, as this has been the main driver of LA's market growth.

As part of the efforts to scale-up and commercialize this technology, this thesis examined its technical and economic feasibility to produce polymer-grade LA (99%) in the U.S. and India. First, the process from feedstock to end product was designed and simulated to determine mass and energy balances, utility costs, and equipment costs, as described in Chapter 3. In this study, the method of esterification-hydrolysis with reactive distillation was adopted among available separation and purification technologies. Based on the process simulation results, this work modeled the economic costs and profitability, including Fixed Capital Investment (FCI), Total Capital Investment (TCI), Total Product Cost (TPC), and Net Present Value (NPV). Further, Monte Carlo simulations were incorporated into the baseline models in order to take into account the impact of irreducible uncertainties on economic viability.

The distribution profiles of FCI, TCI, TPC, NPV under the baseline scenarios are presented in Chapter 5. The expected values of NPV were estimated to be USD 1.95 million and USD 1.31 million, respectively in the case of the U.S. and India. While much more capital is required to operate a plant in the U.S., mainly due to higher machinery prices and labor costs, it is also expected to generate extra revenue from landfill tipping fees, enough to compensate high capital and operating expenses. Further, a sensitivity analysis was conducted to investigate how the profitability is affected by the number of unskilled operators, which is likely to change depending on the quality of feedstock received. It was found that, in the case of India, the NPV stayed positive (USD 0.74 million), even when the number of unskilled staff members was doubled from 12 to 24, in contrast to the U.S. Moreover, the economic performance was found to be significantly improved under lower discount rates, which suggests that project-specific or financing risks should be minimized.

For more comprehensive assessment of the technology, different scenarios were evaluated for economic viability, in terms of technology performance and targeted applications (Section 5.4). By varying the concentration of LA generated in the bioreactor, it was revealed that the improvement of technology performance could significantly enhance the NPV, while it could drop below zero at the concentration of 37-38 [g/L]. Moreover, the comparative study between three different applications (animal feed, food/beverage, PLA) showed that the production of animal feed requires much less capital (approximately USD 0.43M for TCI) and still generates some profits. This result suggests that this application could be used as an intermediate step to prove the technology at an industrial scale, before moving toward the most profitable application with high capital and operating expenses. Finally, based on the results and insights gained in this study, a Technology Commercialization Assessment

Matrix (TCAM) was proposed as a framework for assessing the economic viability and commercial potential of a novel technology with various potential applications (Section 5.4.3).

6.2 Future Work

In this study, guided by experimental results, the profitability of a novel LA production process from organic waste was investigated, with the ultimate goal of commercializing the lab-scale technology. While the results shown in this thesis are positive, there are still remaining steps that need to be taken before a successful scale-up and implementation can be achieved. From a practical standpoint, a pilot-scale plant with a feedstock capacity of 2 to 5 tons first needs to be built to demonstrate the technical feasibility and reliability of the process on a larger scale. Considering the high capital and operating expenses in the U.S. and high risk associated with new technologies, it is recommended that the first pilot-scale plant be implemented in India for the production of animal feed without separation and purification units. This step could also serve as a proof-of-concept for the LA production process, with much lower capital costs due to the lack of the distillation unit operation. In India, however, extra steps are required due to different environmental conditions (temperature, humidity, etc.) as well as infrastructure and, to a lesser degree, available laboratory facilities. Initially, the microbial technology developed at MIT needs to be tested under local conditions using organic waste generated in India. This is primarily because the technology performance might be significantly affected by various feedstock properties discussed above. During this step, technical skills and knowledge must be transferred to local developers and operators in India for successful implementation. At the same time, these commercialization steps need to be supplemented by additional research. First, the sensitivity of plant capacity to TCI, TPC, and NPV could be examined, which will help to determine the future implementation plan. Secondly, for the production of food-grade LA, the process - especially separation and purification - could be further investigated and redesigned in order to improve the profitability. Lastly, as mentioned previously, the environmental and social impact that this technology could potentially make are increasingly important and thus need to be examined in the future. In particular, life-cycle assessments (LCA) could be conducted to evaluate and compare the environmental impacts among different applications.

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