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Feasibility Study and Aspen Plus Simulation for the Manufacture of Virgin Polylactic Acid (PLA) Resins via Ring-Opening Polymerization: a Pilot Plant Proposal in the Philippines

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Globally, plastic pollution has become a major concern environmentally due to its affinity to degrade for generations. The Philippines is known to be the 3rd ranking contributor to plastic pollution in the world as around 2.7 Mt of plastics are generated yearly. A large portion of these non-biodegradable plastics enter the oceans which negatively impacts marine life and even the livelihood of vulnerable coastal communities. From this perspective, biodegradable plastics have been introduced to remedy the problem, and polylactic acid (PLA) has been known to be both biobased and biodegradable, with good mechanical qualities, biocompatibility, low toxicity, and high compostability. PLA is produced by using lactic acid as the main raw material in the process which involves 3 stages: pre-polymerization, lactide formation, and ring-opening polymerization (ROP). This study seeks to design, simulate, and establish a polylactic acid production plant in the Philippines and evaluate its economic feasibility. Using Aspen Plus v11 as a plant design simulation software, the final product has a desirable weight-average molecular weight of 261,364.22 g/mol in the form of pellets for further use. From the results of the feasibility study of this plant design, the simulation can produce about 30,000 t of PLA which will be exported to China, South Korea, Italy, and Belgium. Financial calculations for this pilot plant proposal have been proven to provide a high return of investment at 28.15 % with a short payback period of 5 y.

1. Introduction

Synthetic plastics have been widely utilized in packaging due to their lightweight nature, affordability, and exceptional durability. However, the escalating production of petroleum-derived plastics has led to significant environmental challenges globally especially to various coastal and marine habitats as the number of different sizes of plastics such as microplastic varied from 0.001 to 140 particles/m^3 in water and 0.2 to 8,766 particles/m^3 in sediments. Whereas the frequency at which marine and coastal microplastic accumulation varied from 0.1 to 15,033 counts. This can cause entanglements, poisoning from ingestion, asphyxia, starvation, etc. which are examples of ecological repercussions to organisms due to such an increase in pollution (Thushari and Senevirathna, 2020). This issue is particularly pertinent in the Philippines, ranking third among contributors to plastic pollution, with annual production ranging from 2.7 Mt to 5.5 Mt. Estimates indicate that by 2040, the mismanaged plastic waste in the country could nearly double from 5 to 9 Mt.

In response to the environmental concerns associated with traditional plastics, bioplastics have emerged as a promising alternative. Bioplastics, derived from renewable resources and characterized by biodegradable polymers, offer potential solutions. Notably, polylactic acid (PLA) has garnered attention for its bio-based and biodegradable properties, finding applications in diverse sectors including biomedical and food packaging. PLA is particularly suitable for single-use food packaging due to its rapid degradation at around 58 °C under commercial composting conditions (Jem and Tan, 2020).

PLA production boasts energy efficiency, consuming 25 % - 55 % less energy than petroleum-based polymers, with the potential for further reductions in the future. The predominant method for PLA synthesis involves ring-

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opening polymerization (Rahmayetty et al., 2017), a process governed by racemization and lactide purification. This process includes pre-polymerization, lactide formation, and ring-opening polymerization stages, producing high molecular weight PLA suitable for packaging applications (Jamshidian et al., 2010).

In 2014, the University of the Philippines – Mindanao conducted a program to produce their lactic acid, which is a fundamental component of PLA, from starch at a technical grade using their current technology. The produced lactic acid currently provides no commercial use unless it is purified and/or converted into PLA for more viable uses (DOST-PCIEERD, 2019). In the Philippines, no companies manufacture PLA, and the country relies entirely on imports. This presents an opportunity to capture the PLA market and substitute existing plastics like polyethylene terephthalate, polystyrene, and polypropylene with PLA since House Bill 9147 of the Philippines aims to oversee the production, importation, sale, distribution, provision, use, recovery, collection, recycling, and disposal of single-use plastic products in the country.

The main objective of this plant design is to propose a pilot plant for producing virgin polylactic acid (PLA) resins in the Philippines by assessing the PLA market, identifying the optimal process and location using Visual PROMITHEE, and evaluating its overall economic feasibility. The contents of this paper provide a detailed outlook towards establishing the very first virgin PLA manufacturing plant situated in the Philippines.

2. Market Study

In 2019, the global demand for PLA was projected to reach around 400,000 t, marking a substantial rise from the estimated 120,000 t. This surge in demand was initially forecasted in 2013 under Jem's Law, which suggests that the global demand for PLA doubles every 3 to 4 y. Jem and Tan (2020) present in their study the growth trend of PLA with an annual growth rate of 26 % versus the global PLA plant capacities and the available countries that manufacture PLA. In 2018, the demand for PLA was higher compared to the global PLA plant capacity and it continued to increase up to the year 2021. Companies such as SuPLA, COFCO, and Total-Corbion do not yet fully meet the market demand due to different reasons. As a result, the supply for PLA becomes short and the pricing would increase to around 20 % - 50 % since 2019. Future market growth slowed down significantly as a result of the PLA and bioplastic-related market and applications.

The global PLA market is composed of six major regions, namely: Asia-Pacific, Europe, Latin America, North America, Middle East, and Africa. Among all regions, Asia-Pacific is expected to be the fastest-growing regional market in the succeeding years due to the continuous development in the packaging sector. Furthermore, Europe also shares the largest PLA market followed by North America and Asia Pacific (Balla et al., 2021).

Figure 1 shows the end-use industry of PLA market in 2021. The packaging sector dominated the PLA market. The packaging segment accounted for more than half of the PLA market in 2021 in terms of revenue. A study by Ranakoti et al. (2022) has stated that PLA is segmented into different applications such as packaging. The inclination towards renewable and sustainable packaging and the increasing ecological awareness throughout the world are driving companies to use numerous PLA packaging solutions.

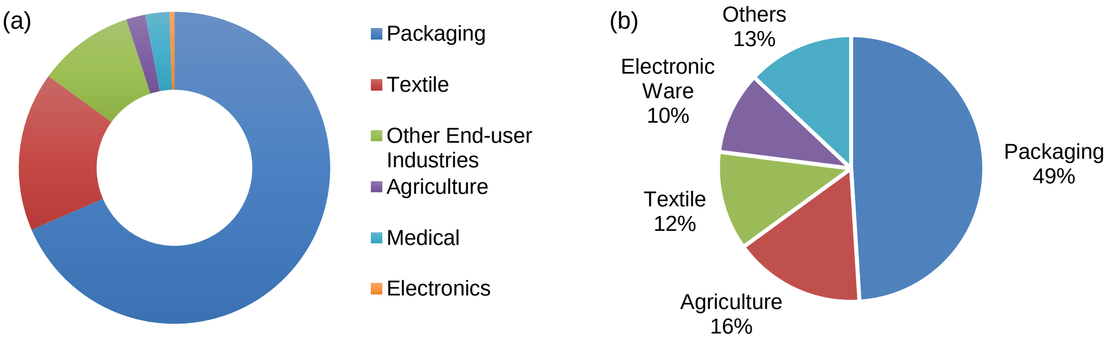

Figure 1: (a) End-user Industry Segment of PLA Market and (b) Share of PLA Applications in 2021.

The accepted forecast of the supply and demand trend of PLA is based on the importation and exportation of China, South Korea, Italy, and Belgium which were retrieved from United Nations (UN) Comtrade. There were several projection equations used to get a proper correlation of the market data. The polynomial 2^{nd} order has the highest R^2 calculation and is considered the most adequate forecast for the demand and supply trend as depicted in Figure 2. The total production capacity of the manufacturing plant was determined based on the demand in the four countries targeted for product export, as the demand for PLA in the Philippines remains insufficient for accurate forecasting. Both supply and demand were projected from 2010 to 2029, indicating a significant increase over this period.

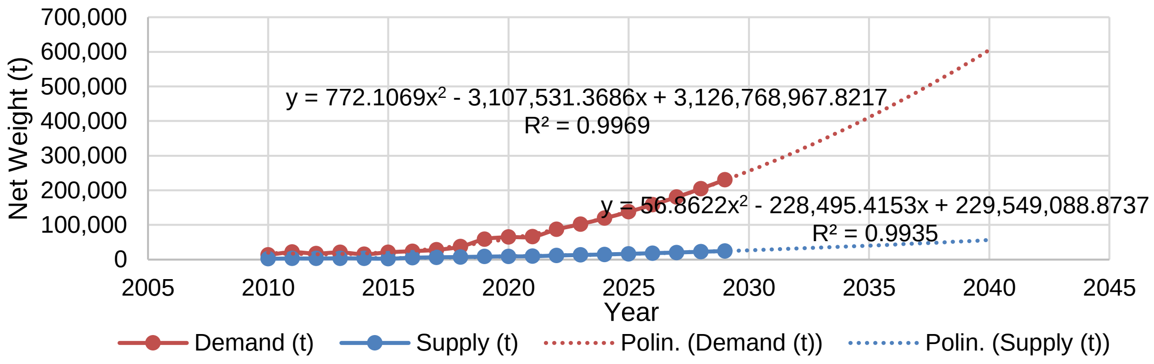

Figure 2: Accepted Forecast of the Supply and Demand trend of PLA.

Table 1 illustrates the demand for PLA indicated in the third column, alongside the corresponding target market share percentages in the second column. The total annual plant capacity for PLA production, sourced from imports in China, South Korea, Italy, and Belgium, stands at precisely 30,032 t.

Table 1: Plant Capacity of PLA based on PLA imports in China, South Korea, Italy, and Belgium

Country	Market Share Percentage	Demand (t)	Market Share (t)	Total Plant Capacity (t)
China	15 %	80,086	12,013	30,032
South Korea	15 %	29,912	4,487	
Italy	13 %	72,258	9,394	
Belgium	13 %	31,830	4,138	

3. Technical Study

3.1 Process Selection

The Visual Preference Ranking Organization Method for Enrichment Evaluation (Visual PROMETHEE) is a decision-making technique that ranks alternatives based on multiple criteria. It involves identifying criteria, normalizing them for comparability, constructing preference functions, and conducting pairwise comparisons to determine preferences. Visual PROMETHEE aids in decision-making by aggregating preferences across criteria and providing a ranked list of alternatives. It offers a structured approach to consider various factors and preferences, facilitating informed and transparent decision-making processes.

Three different processes to produce PLA were compared using Visual PROMETHEE to select the most suitable process available: Direct Polycondensation, Azeotropic Dehydrative Condensation, and Ring-Opening Polymerization. Furthermore, selecting the best process requires a criterion based on significant process parameters and weights following its significance. The process parameters and respective weights are as follows: Molecular weight (25 %), Product Yield (25 %), Complexity (15 %), Purity (15 %), Environmental Impact (10 %), and Operating Conditions and Requirements (10 %). Historically, process design has focused on techno-economic factors, with safety considered later. Park et al. (2022) suggest that safety is largely predetermined in the design phase, including technology and configuration choices. Alterations at later stages can be costly and complex which means safety engineers consider to integrate all operating conditions and requirements into the initial design to ensure optimal process safety.

Following Figure 3a, the results show that the most favorable process for PLA production is Ring-opening Polymerization through lactide formation, followed by Direct Polycondensation of lactic acid. The least favored method is the Azeotropic Dehydrative Condensation of lactic acid. Among the three processes, Ring-Opening Polymerization is the most preferred method for synthesizing PLA on a large-scale due to its better reaction control in producing high molecular weight PLA. The proposed name of this production plant to be put up in the Philippines is PLAsteco Manufacturing (PLAsteco Mfg).

3.2 Plant Location Selection

Towler and Sinnott (2013) stated that the location of the plant has a crucial effect on the feasibility of the project and the scope for future expansions. The basis of the land area requirement for PLAsteco Mfg is the Polylactic Acid production plant in Thailand, TotalEnergies Corbion. The production capacity of TotalEnergies Corbion is 75,000 t, with a total land area of 5.75 ha. Utilizing Eq(1), given that the production capacity of PLAsteco Mfg is about 30,032 t, the proposed plant size is approximately 2.30 ha.

$$\frac{\text{Plant Capacity}_{\text{Basis}}}{\text{Land Area}_{\text{Basis}}} = \frac{\text{Plant Capacity}_{\text{Actual}}}{\text{Land Area}_{\text{Actual}}} \quad (1)$$

Three available industrial lands were chosen from, all of which are situated at a Philippines Economic Zone Authority (PEZA): Light Industry & Science Park (LISP) III in Sto. Tomas. Batangas, Hermosa Ecozone Industrial Park (HEIP) in Hermosa, Bataan, and TECO Industrial Park in Mabalacat, Pampanga. There are multiple factors to consider when selecting a suitable plant location, which includes the following: Proximity to Raw Material, Land Cost, Electricity Supply Cost, Water Supply Cost, and Labor cost. Like the method of process selection, Visual PROMETHEE was used to evaluate it which uses the appropriate data per criterion as depicted in Figure 3b for the plant location selection. Based on the evaluation, the available industrial land at HEIP in Bataan is the most ideal location to build the PLAsteco Mfg plant.

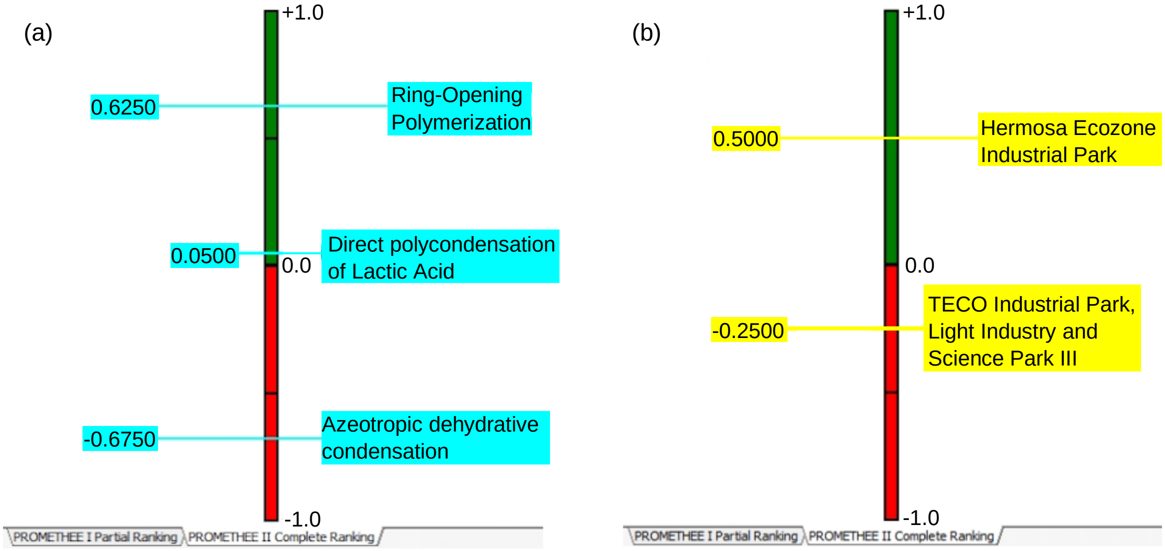

Figure 3: Visual PROMETHEE Complete Ranking for (a) Process Selection and (b) Plant Location Selection

3.3 Process Specifics

Adapted from Rivadulla (2019) with some modifications, the PLAsteco Mfg facility undertakes the conversion of lactic acid into polylactic acid through a continuous production process operating 340 d annually. The plant comprises four sections simulated in ASPEN Plus V11: Lactic acid purification and Pre-polymerization, Lactide formation and purification, Ring-opening Polymerization, and Utilities Section.

Beginning with a raw material of 86 %wt L-(+)-Lactic Acid stored at 1 atm and 25 °C, the process progresses with a concentration step facilitated by an evaporator EVAP-101, aimed at purifying the lactic acid by removing volatile impurities under vacuum conditions at 95 °C and 6.5 kPa. The concentration process elevates the lactic acid content to 93.30 % by mole or 98.54 %wt, crucially mitigating hydrolysis risks in subsequent polymerization stages.

Afterwards, the concentrated lactic acid undergoes pre-polymerization in a pre-polymerization reactor R-101, a Continuously Stirred Tank Reactor operating at 180 °C and 101.325 kPa. The resulting liquid-melt phase of the lactate acid oligomers is then blended with a Stannous Octoate catalyst in a mixing tank MIX-201, before entering in a depolymerization reactor R-201, operating under similar conditions at 220 °C and 101.325 kPa. At this point, lactide and oligomers are produced, necessitating separation using another evaporator EVAP-201 operating under vacuum at 220 °C and 2.5 kPa. The vapor stream, containing 63 % lactide by mole, is isolated, while the liquid fraction is recycled through a purge stream to prevent catalyst accumulation and potential side reactions.The purified lactide is further processed in a mixer, where a catalyst system is introduced before entry into a ring-opening polymerization reactor R-301. R-301 operates as a plug flow reactor at 180 °C, optimizing lactide conversion to polylactic acid. The PLA melt stream undergoes purification in a phase-separator S-301, operating at 180 °C and 2 kPa, effectively removing residual volatile components such as lactide which then results to 99 % by mole of PLA. The exiting stream of S-301 would then be pumped to a twin-screw mixer extruder X-301, where the stabilizer and deactivating agents are added. Ideally, to mitigate the detrimental effects of catalyst residues on PLA polymer quality, a deactivating agent, phosphoric acid, is introduced during processing. Stabilizers are added to maintain molecular weight integrity. The molten PLA is extruded through a die to form strands then subsequently cooled and granulated into pellets for downstream processing in a plastic pelletizer PEL-301.The resulting PLA resin from the manufacturing simulation has a desirable weight-average molecular weight of 261,364.22 g/mol and a degree of polymerization of 3,627.04. These properties make it suitable for various applications in industries that prioritize sustainability and biodegradability.

4. Financial Feasibility

The land cost was calculated prior using Eq(1), while the rest of the expense computation of the manufacturing facility was based on Towler and Sinnott (2013). Cost-estimating techniques utilize historical data and cost indices, comparing present costs to past costs, based on labor, materials, and energy costs published in the aforementioned reference. A composite index for the U.S. process plant industry is published monthly in the journal Chemical Engineering; this is the Chemical Engineering Plant Cost Index (CEPCI), often referred to as the CE Index. Cost was evaluated in US Dollar (USD) and were then converted to Philippine Peso (PHP). All the pertinent costs calculated are presented in Table 2.

Table 2: Summary of Overall Plant Costs.

Cost	Parameter / Specifics	Value (PHP)	Total (PHP)
Total Fixed Capital Investment	Inside Battery Limit	570,659,635	1,503,606,828
	Outside Battery Limit	225,139,421	
	Design and Engineering Cost	113,787,069	
	Contingency Charges	113,787,069	
	Land Cost	138,162,000	
Variable Costs of Production	Raw Materials Expenses	3,371,098,500	3,459,092,962
	Consumables Expenses	59,629,164	
	Electricity Expenses	696,796	
	Water Cost	1,100,577	
	Fuel Cost	52,574,476	
	Shipping and Transportation Costs	63,993,449	
Total Fixed Cost of Production	Operating Labor Cost	56,251,408	151,204,596
	Direct Salary Overhead	35,157,130	
	Maintenance Cost	27,381,938	
	Real Property Tax	1,685,564	
	Insurance Cost	11,378,707	
	Utilities (Electricity and Water Costs)	18,686,813	
	Running License Fees and Permits	423,060	
	Telecommunication Expenses	239,976	

Table 3: Income Statement of PLAsteco Mfg.

Year	Plant Capacity	Revenue (M PHP)	Total Cost of Production (M PHP)	Depreciation (M PHP)	Taxable Income (M PHP)	Income Tax (M PHP)	Income (Net Profit) (M PHP)	Cumulative Income (M PHP)
0	-	-	-	-	-	-	-1,504	-1,504
1	-	-	-	-	-	-	-1,504	-1,504
2	-	-	-	-	-	-	-1,504	-1,504
3	70 %	3,460	2,677	137	646	0	646	-857
4	85 %	4,201	3,232	123	846	0	846	-11
5	100 %	4,943	3,787	111	1,045	0	1,045	1,034
6	100 %	4,943	3,787	100	1,056	0	1,056	2,091
7	100 %	4,943	3,787	90	1,066	0	1,066	3,157
8	100 %	4,943	3,787	81	1,075	0	1,075	4,231
9	100 %	4,943	3,787	73	1,083	0	1,083	5,315
10	100 %	4,943	3,787	65	1,090	55	1,090	6,405

When cash inflows are not balanced, there is a need to calculate the cumulative net cash flow for every period and then utilize Eq(2) to get the payback period:

$$\text{Payback Period} = A + \frac{B}{C} \tag{2}$$

where A is the last period number with a negative cumulative income, B is the absolute of cumulative net cash flow at the end of period A, and C is the total cash inflow during the period following period A.

A cumulative net cash flow is the difference between the sum of the inflows to date and the initial outflow. As seen in Table 3, year 4 has the last negative entry specific to the cumulative income, which means it will represent A in Eq(2). Referring also to year 5 in the same table, B is calculated as 1,056 M PHP minus 10.74 M PHP, while C being 1,056 M PHP, which results to a payback period is 4.99 or about 5 y.

According to Towler and Sinnott (2013), return on investment (ROI), which can be calculated using Eq(3), is another simple measure of economic performance, with ROI at year 5 being 28.15 %.

$$\text{ROI (at year 5)} = \frac{\text{Net annual profit}}{\text{Total investment}} \text{ x } 100\ \% \qquad (3)$$

5. Conclusion

This study was able to simulate the planning and development of an economically feasible polylactic acid production plant in the Philippines. Simulations made with ASPEN Plus v11 and Visual PROMETHEE project a promising market picture in which the Philippines has a potential to capitalize on the PLA market share, thus projecting positive economic growth. To meet market expectations for high molecular weight PLA, ROP through lactide formation was determined to be the best process selected out of different PLA formation processes. The process produced approximately 30,000 t of PLA with a desirable weight-average molecular weight of 261,364.22 g/mol. Given this, Bataan was evaluated to be the best site location which can accommodate PLA production using this process. The positive cumulative income and full plant capacity after five years justify the economic viability of a PLA production plant in the Philippines. For sustainable production, securing nonconventional renewable resources like sugarcane and exploring agricultural waste potential is recommended. Expanding PLA production in the Philippines is key to meeting global market demand.

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