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Lactic Acid Production from Cow Manure: Technoeconomic Evaluation and Sensitivity Analysis

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Abstract: Recently, the industrial focus has shifted to renewable raw materials due to the exhaustion and rising pressures about environmental and political issues. Lignocellulosic biowaste can be derived from a range of sources, such as animal manure, forestry waste, and agricultural waste, and it can be transformed into lactic acid through a biochemical process. There are 942.63 million cattle in the world and annually generate 3.7 billion tons of manure, which could be used to produce lactic acid. The economic viability of a lactic acid plant from cow manure has not yet been determined and is, thus, considered in this study. Using the modeling program Aspen Plus data and other sources, as well as collecting all economic inputs, the feasibility analysis of a lactic acid plant handling cow manure is assessed in this paper. Three scenarios are calculated to check the feasibility depending on the plant size: scenario I handles 1,579,328 t·year^{-1}, scenario II handles 789,664 t·year^{-1}, and scenario III handles 315,865 t·year^{-1}. The results demonstrate that treating the tested lignocellulosic biomass for the manufacture of lactic acid is economically feasible because the economic analysis shows positive net present values for scenarios I, II, and III. The technoeconomic analysis reveals that the minimum lactic acid selling price for scenario I is 0.945 EUR·kg^{-1}, which is comparable to the cost of commercial lactic acid produced from starch feedstock. Scenario II achieves a minimum selling price of 1.070 EUR·kg^{-1}, and scenario III 1.289 EUR·kg^{-1}. The sensitivity analysis carried out reveals that the factor with the biggest impact on the NPV is the yield. Moreover, this study provides a model of industrial application and technoeconomic evaluation for lactic acid production from cow manure.

Keywords: lactic acid fermentation; cow manure; sensitivity analysis; technoeconomic analysis; plant design

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1. Introduction

One of the most significant organic acids, lactic acid (LA), is widely utilized globally in a variety of industrial and biotechnological applications. There has been a growth in study interest in the value of natural materials for LA production, since they are inexpensive, plentiful, and readily available throughout the year, especially in light of the global economic and lactic acid consumption challenges. Recent developments showed that fermentation-based lactic acid production is preferable to chemical methods due to contemporary environmental concerns, such as greenhouse emissions or using refined sugars. Many raw materials or byproducts from agriculture and agroindustrial sources can be processed in an environmentally benign manner and are fermentable, which makes them appealing candidates for fermentation biotechnology to produce a value-added product with a variety of uses. Moreover, significant progress was already been achieved in recent years to obtain pure lactic acid with the best production results [1]. Estimations show that approximately 130,000 to 150,000 tons of lactic acid are going to be required annually [2],

and in the near future, it is likely that lactic acid usage is going to rise quickly on a global scale [3].

Cow manure is a widespread waste product that is complicated to recycle. Manure from intensive animal farming can oversaturate neighboring soils and water bodies with nutrients if it is not properly handled. There are 942.63 million cattle around the globe, and it is estimated that they can generate 3.7 billion tons of manure annually. The primary source of nutrition for these cows is cellulosic materials. Consequently, lignocellulose represents a significant portion of cow manure. Utilizing such lignocellulosic fractions as the starting material for various fermentative processes allows for its valorization. This percentage has the ability to be converted into sugar, which can then be utilized to feed lactic acid bacteria (LAB). Lactic acid, which is produced by LAB, can be polymerized to create poly(lactic acid), a bioplastic with a bright future [4].

Lactic acid is used for producing hygiene and cosmetic products in the cosmetics industry because of its moisturizing, antibacterial, and renewing properties on the skin. It is also used to make products for oral hygiene [5]. It is utilized as an additive in the pharmaceutical sector to create dermatologic treatments and medications for osteoporosis [6]. In the culinary, pharmaceutical, cosmetic, and textile industries, lactic acid (LA) is employed as an acidulant and a preservative [7]. In the baking industry, it serves as a precursor in the manufacturing of emulsifiers such stearoyl-2-lactylates. It performs a wide range of roles, including flavoring, regulating pH, acting as an acidulant, enhancing microbiological quality, fortifying minerals, and extending shelf life [3].

Simulation and economic analyses have an important role during the evaluation and/or design of chemical plants, as well as in reducing economic losses in a given process, since it can reveal, at different scales, whether the process can deliver (or not) profitable results in the future. Moreover, the sensitivity analysis is a useful tool usually used to estimate the influence of different input factors on selected output variables. Therefore, the application of a sensitivity analysis to determine the profitability of an investment can be established as an essential technoeconomic study in order to measure the performance and productivity of a chemical project, thus, allowing for the initial identification and future prediction of eventual problems of any kind that could emerge during the execution of the project [8].

Even though lignocellulosic biomass transformation to lactic acid has been the subject of extensive research [9–11], it is still unclear if a lactic acid facility with cow manure as a raw material would be economically viable. This is the first study to technoeconomically evaluate the manufacturing of lactic acid utilizing cow manure as a raw material, providing a design case for commercial-scale production.

2. Materials and Methods

2.1. Raw Material and Strain

Cow manure is a waste product and has a high lignocellulosic fraction, which could be used as a raw material to produce lactic acid. As shown in Table 1, 51.5% of dry matter is hemicellulose plus cellulose, which can be transformed into sugar.

The cellulose and hemicellulose composition of cow manure, similar to commonly used lignocellulosic materials that also have a low lignin content, makes it a biodegradable material with great potential to obtain lactic acid. The production of lactic acid from this material in a saccharification and fermentation (SSAF) process reached productivity and yield values in the range of fermentations that use high-grade sugars or lignocellulose as a raw material [12].

Cattle distribution worldwide is not uniform, but concentrated in certain locations. For example, in Europe, Germany, France, and the United Kingdom are the countries with more heads of cattle, as seen in Figure 1.

Table 1. Dry cow manure lignocellulosic material analysis. Adapted from [12].

Stable	Hemicellulose (%)	Cellulose (%)	Lignin (%)	Ash (%)	Humidity (%)
Manure heap A *	27.3	24.5	3.8	17.69	2.32
Manure heap B *	26.3	25	3.8	18.85	2.5
Farm 1A	28.3	23.4	3.5	18.04	2.32
Farm 1B	30.2	21.7	3.1	17.43	2.11
Farm 2A	28.4	23.6	4.1	17.13	2.76
Farm 2B	28.3	22.9	5.3	16.5	2.23
Average	28.1	23.5	3.9	17.6	2.4

* A and B imply different locations where the waste was collected.

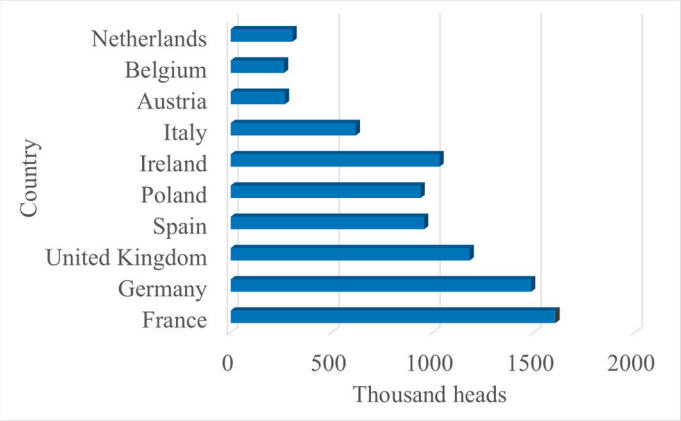


Figure 1. Ten countries with more heads of cattle in EU27 in 2023.

Locally, per country, distribution is not uniform; instead, there are certain areas where production is concentrated [13–15]. A theoretical distance of 100 km around a plant can be traced where all the raw material would be collected. The calculated production capacity per head was 4 tons per year [16].

The estimation of worldwide cattle livestock in 2023 was 942.63 million heads, with a waste production of 3770.52 Mt per year [17]. Cow manure has a value, so it was supposed in this study that local farmers would be paid. Price is volatile, as is the sector [18,19]. For this study, a conservative price of 5 EUR per ton was considered, according to [20–22] and local markets. The transport cost was calculated as an average of a total 100 km, the price assumed according to [23] and local market prices.

The dry-milling biorefinery-processed cow manure with the strain *Bacillus coagulans* DSM2314 was predicted to produce lactic acid with a productivity of 13.5 $g \cdot L^{-1}$ and a yield of 33.3%.

2.2. Process Model Simulation and Scenario Design

As cattle concentrations are located in certain areas, one hundred kilometers around the plant, cow manure availability was used to model a factory with a processing capacity, according to Table 2. Scenario I considered an area of 100 km with approximately 395,000 heads of calves, which can be found in different areas in Europe [13–15].

On-site processing (grinding and drying) was estimated to result in a weight reduction in cow manure by 50%, according to laboratory experiences [12]. The facility had a 20-year lifespan, which included a year for building and startup. The operating mode was set to a continuous mode during each of the 8460 operation hours per year. Calculations for the mass and energy balances were determined using Aspen Plus, based on the national renewable energy laboratory (NREL) model [9], adapting it when necessary. Microsoft

Excel 2016 was used to carry out the profitability, discounted cash flow, sensitivity analysis, and the rest of the economic analysis.

Table 2. Cow manure capacity treatment for different scenarios.

Parameter	Scenario I	Scenario II	Scenario III
Plant capacity (t) Cow manure per year	1,579,328	947,597	315,866
Capacity treated (%)	100	50	20

Different plant capacities were calculated in order to analyze the plant's impact on feasibility. The plant capacity for each considered scenario is defined in Table 2, and the plant was dimensioned and quoted according to it. Equation (1) was used to calculate the purchase price of a specific type of equipment ($C_{p,0}$) with a different characteristic size (X) in a different year (t):

$$C_p = \frac{CEPCI_t}{CEPCI_{t0}} \cdot C_{p,0} \cdot \left(\frac{X}{X_0}\right)^n \quad (1)$$

where $CEPCI_t$ is the chemical engineering plant cost index at year t published monthly in the Chemical Engineering Magazine and the exponent (n) is characteristic to the particular type of equipment. In this study, the exponent (n) was set to be 0.6 (sixth-tenths factor rule) for the order-of-magnitude estimation of the new equipment cost [24].

2.3. Process Design

2.3.1. General Process

To establish the technological viability of the process simulated in this work, it was previously investigated [8] and demonstrated at laboratory scale [12]. Aspen Plus software version 13 data [25] were used to simulate the process model, validated with laboratory experiences. An overall equipment efficiency (OEE) of 85% was taken for the whole process, according to [26].

The NREL design for the manufacture of ethanol from maize stover was used as the base process [9]. The overall flowsheet of the current model, shown in Figure 2, was similar to the NREL model, in that it had eight sections, including the feedstock handling, pretreatment, biodetoxification, enzymatic hydrolysis and fermentation, product recovery, wastewater treatment, residue combustion, storage, and utilities system. The main variations from the NREL model were discussed next, and the main points are illustrated in Table 3:

1. To fulfill the bovine waste management needs, area A1 handled 2077 metric tons of dry bovine manure per day at scenario I, as opposed to the 2000 tons in the NREL model, when constructed at 100% capacity.
2. In area A2, the dry dilute acid pretreatment method was applied with 8% of cow manure solids and 33% of dilute sulfuric acid solution (5% sulfuric acid in weight percentage). Solid–liquid separation using flash-cooling was required. This area included ammonia conditioning on liquid pretreatment hydrolysate, as per the NREL design.
3. Simultaneous saccharification and fermentation: enzymatic hydrolysis at 30% (*w*/*w*) solid content and lactic acid fermentation using *Bacillus coagulans* DSM2314 were used in area A3, while separate ethanol fermentation and hydrolysis (SHF) at 20% solid content were used in the NREL 2011 design. Only one fermenter was needed to achieve the production capacity, instead of five as in the NREL design. The size changed depending on the scenario.
4. Instead of the two-column ethanol distillation and one-column molecular sieve absorption in the NREL design, area A5 used centrifugation, precipitation, and separation [27].

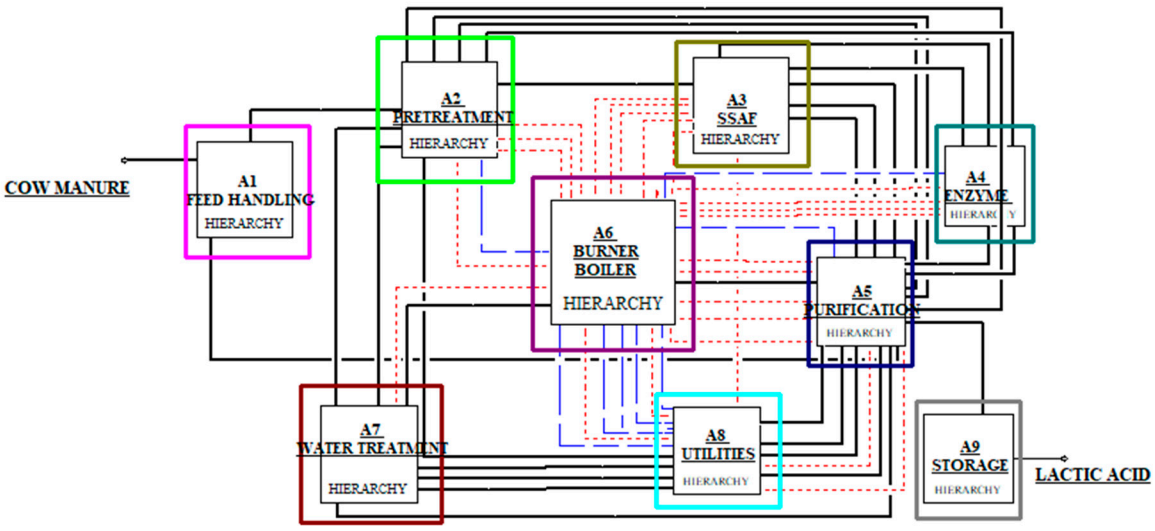


Figure 2. Flowchart for the Aspen Plus platform cellulosic lactic acid synthesis process using cow manure as feedstock.

The model kept the other process areas the same, such as area A4 for enzyme production, area A6 for residue combustion, area A7 for storage, area A8 for wastewater treatment, and area A9 for utilities.

Table 3. Main process parameters.

Parameter	Cow Manure Model	Reference
Pretreatment		
Sulfuric acid loading	1.25% per mg·g^{-1} dry biomass	[12]
Temperature	120 °C	
Pressure (MPA)	1	
Residence time	2 h	
Total solids loading	8% (*w*/*w*)	
Detoxification	Ammonia conditioning	
SSAF		
Strain	*B. coagulans* DSM2314	
Temperature and residence time	50 °C, 18 h (hydrolysis)	
	50 °C, 48 h (SSAF)	
Total solids loading	8% (*w*/*w*)	
Cellulases loading	0.19 mL·g^{-1}	
Glucan conversion to glucose (%)	90	[28]
Ethanol and lactate yield from glucose (%)	95	
Ethanol and lactate yield from xylose (%)	85	[29]
Product recovery	92%	[27]
Final product concentration (%)	88% (*w*/*w*) lactic acid	[10]

2.3.2. Front-End Operations

Trucks were used to bring the biomass to the plant (Figure 3). The transportation distance was expected to be 100 km because the plant would be located in an area with enough availability. The facility was anticipated to operate in batch mode 96% of the time, resulting in an annual running time of 8640 h. To minimize the size of each batch, a conveyer belt would move it to the grinder. The grinder would run several cycles for each batch to lower the expense of bigger-scale equipment.

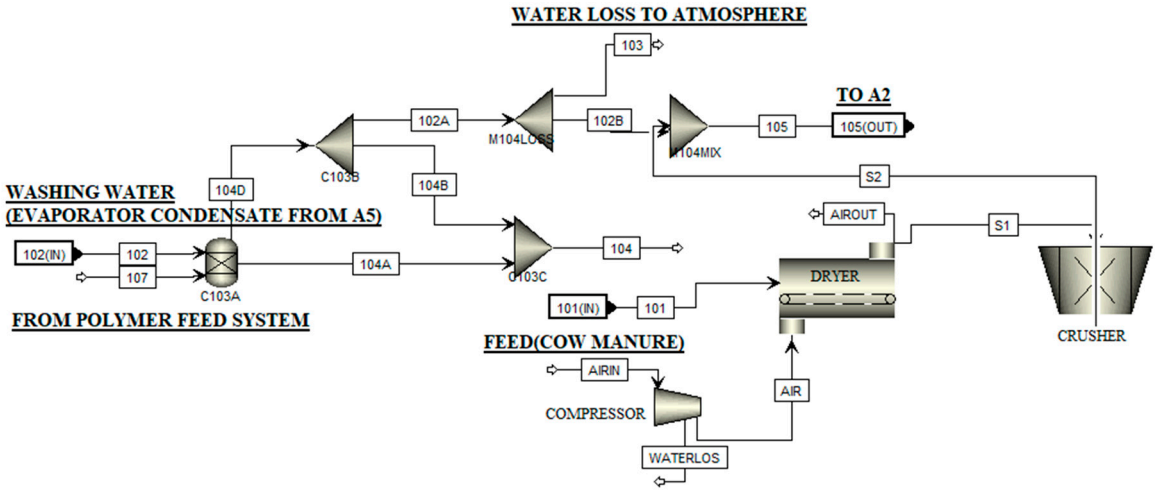


Figure 3. Area A1 flowchart: material reception, drying, and milling.

The total batch duration for cow manure was 48 h, which corresponded to 182 batches handled annually. To operate at scenario I, the batch size was set to 4154 t·batch^{-1} of cow manure, in order to provide the required annual supply. Cow manure could be stored in tanks to make it more widely available, but this would significantly raise the cost; therefore, it was not considered in this study. The cow waste would be gathered from outside sources to save costs. Cow manure would be purchased for 5 EUR per metric ton, resulting in an 11 M EUR yearly expense for raw materials [30]. Other scenarios were discussed below. The number of daily trucks according to the scenario considered is detailed in Table 8.

2.3.3. Pretreatment

The lignocellulosic biomass portion needed to be processed to expose the polysaccharide before the cellulose and hemicellulose could be transformed into hexose and pentose sugars. In a vessel, sulfuric acid and biomass were combined and heat hydrolysis took place. During thermal hydrolysis, cellulose changed into glucose, while hemicellulose changed into xylose.

A pretreatment section equipment overview is shown in Figure 4. The substrate only needed moderate preparation because cow manure has a low proportion of lignin [8]. The cell wall had to be disrupted in order to expose the polysaccharide in cow manure prior to fermentation. The cow manure was initially ground for 60 min [12] to obtain particles between 0.8 and 1.0 mm in size.

The impact of the pretreatment on the effectiveness of lactic acid production from the lignocellulosic source was investigated in various other research works. However, it is unclear which method favors the greatest release of glucose and xylose from the carbohydrate polymers while also being cost-effective [31–33].

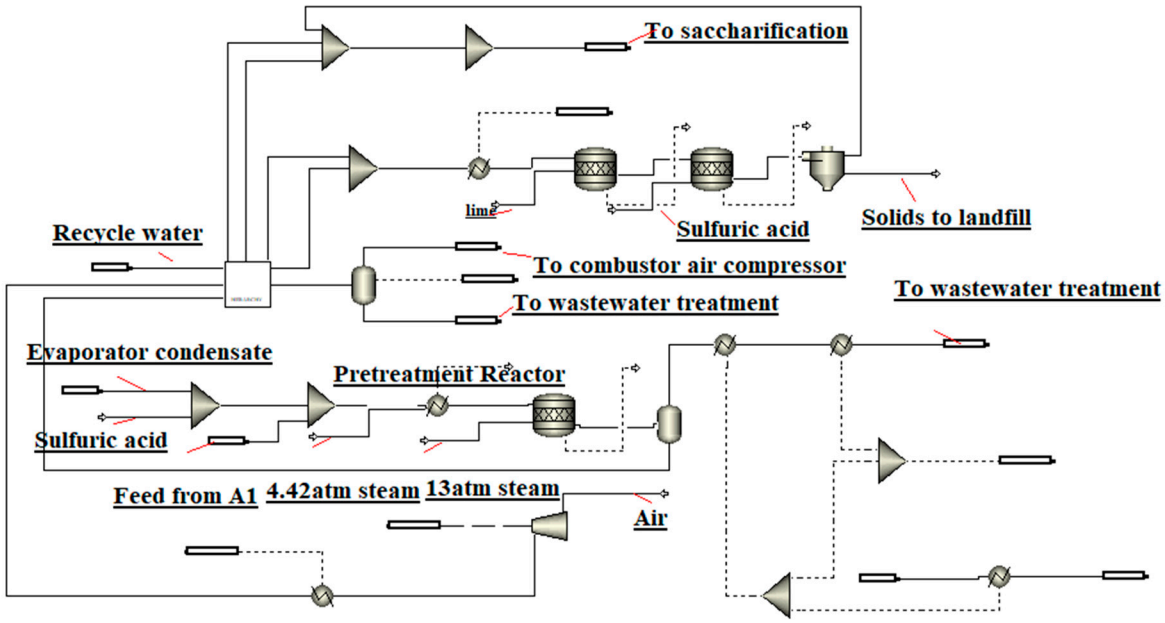


Figure 4. Area A2: chemical pretreatment.

2.3.4. Saccharification and Fermentation

After completing the pretreatment, the solution was moved into the fermentation and saccharification stage. Only one vessel was necessary for the hydrolysis and fermentation of the hexose and pentose sugars because SSAF was used. An efficiency of 33% was expected. In a previous study [12], inhibitors were analyzed in a laboratory and no significant level of byproducts, such as furfurals, was produced during the saccharification process; therefore, they were not considered here. Figure 5 provides an overview of the SSAF section.

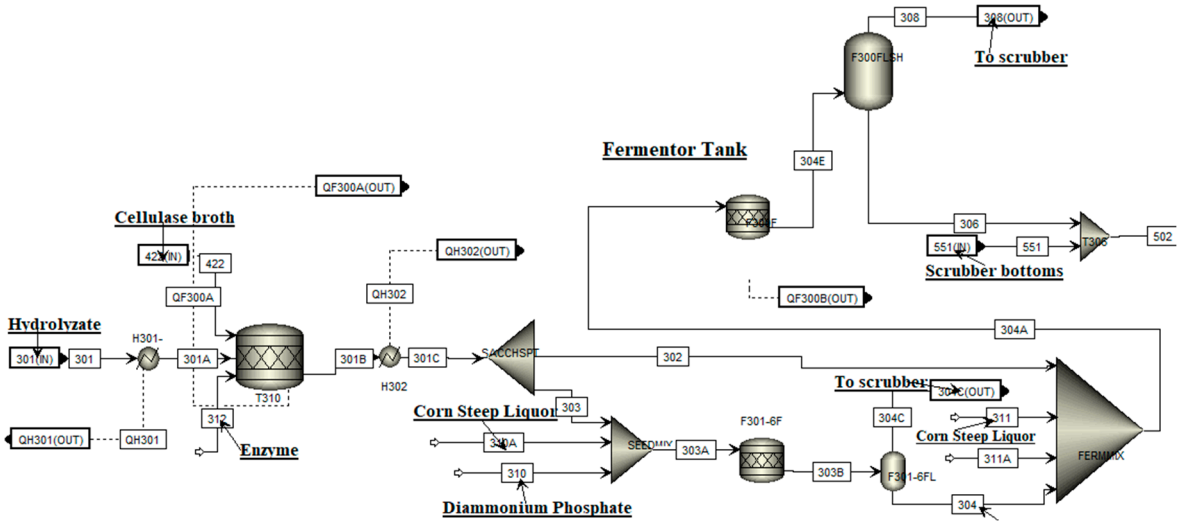


Figure 5. Area A3: saccharification and fermentation.

2.3.5. Lactic Acid Recovery

A flowsheet of the main proposed changes is shown in Figure 6. This procedure produced calcium lactate, an acid salt formed from calcium, by adding more calcium carbonate or calcium hydroxide to the fermenter to neutralize the acid produced and maintain the pH between 5 and 6 [34]. Neutralization was carried out due to the highly protonated form of LA inhibitory effects on cellular metabolism at high LA concentrations

and low pH. LA has the ability to cross cell membranes, which can increase its intracellular concentration and harm the cell membrane [35].

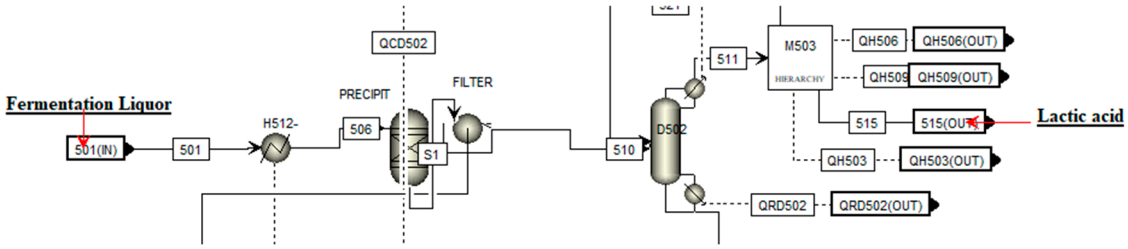


Figure 6. LA recovery main changes flowsheet.

Calcium sulfate or gypsum was precipitated from the fermentation broth using sulfuric acid and was then filtered. To obtain pure LA, the filtrate that contained free organic acid was evaporated. Utilizing precipitation, a LA of technical grade (22% to 44%) was achieved. However, LA with a high thermal stability and purity was needed for applications with a higher level of added value. The technical-grade LA was esterified with either methanol or ethanol to produce a high-purity product. The ester was then recovered through distillation, hydrolyzed with water, evaporated, and the alcohol was recycled [34]. Calcium lactate could be converted to zinc lactate using sulfate or zinc carbonate, and then zinc lactate was recrystallized and dissolved in water to produce pure LA. Zinc was then precipitated as zinc sulfide using a hydrogen sulfide solution [36]. The LA solution was filtered, vacuum evaporated, and clarified with coal. Zinc salt crystallizes better than any other lactate, making it the most appropriate for this procedure [37].

2.4. Economic Assessment

Estimates of the capital cost, operating cost, and revenue generation were used to analyze the economic performance of the studied process. The process was then subjected to profitability, cash flow, and sensitivity assessments for an evaluation and comparison. Indicators of profitability, such as the net production cost, minimum selling price, gross profit, net profit, net present value (NPV), internal rate of return (IRR), payback period, return on investment (ROI), and the break-even point, were also calculated.

As mentioned above, the data for the mass and energy balances were computed using the Aspen Plus simulation, according to the NREL design, which was similar to this process. The simulation data were used to determine the quantity and size of the equipment, chemical use, and utility use. Pumps, conveyors, and evaporators were just a few examples of the general equipment whose prices were quoted using data from the NREL database and other sources [9,38,39]. Chemical prices were retrieved from Humbird et al. [9] and labor costs from [40]. The year 2022 was used as reference. The exchange rate of USD to EUR was set to approximately 1.05, according to the average exchange rate in 2022 [41].

Based on the overall cost of the equipment, the total capital investment was estimated and the plant capacity was used to estimate the variable and fixed operating expenses. A thorough analysis of all the steps necessary to install the appropriate equipment and start its running could be used to calculate the installation cost. The degree of the estimate at this time did not merit this level of information. More information would be required when the project would be significantly closer to building and an estimate with ±5% accuracy would be needed for funding. Many engineering texts [42,43] give installation factors that could be used to calculate the installation cost of the purchased equipment.

The internal rate of the return, payback time, and net present value was the main consideration during the economic analysis. When the NPV and IRR were higher than zero and the payback period was less than the plant operational lifespan, the economic viability was attained. By discounting the future cash flows to the present value, it was

established whether the scenario would be profitable throughout the course of the plant's 20-year life span.

Aspen Plus and other sources [43–45] provided information on the investment, operating costs, and unit production costs. The revenue, gross margin, in addition to the NPV, IRR, and payback period were calculated with Excel. The direct fixed capital, working capital, and start-up costs composed the overall capital investment. The expenses for the raw materials, labor, facilities, laboratories, utilities, and transportation were all included in the operation cost.

Additionally, any potential subsidies were left out, assuming that an investor would provide the necessary funding. The total present value of the annual net income received during the project exploitation term constituted the NPV [46], which was defined as follows in Equation (2):

$$\mathrm{NPV} = \sum_{k=0}^{N} \frac{C_k}{(1+i)^k} \quad (2)$$

where i is the discount rate, n is the term of project exploitation, and C_k is the net income in the kth year of that period.

The IRR is the discount rate in cases where the NPV was zero [47] and was characterized in Equation (3):

$$\mathrm{IRR} = \sum_{k=0}^{N} \frac{C_k}{(1+i)^k} - C_O \quad (3)$$

where C_0 is the total cost of the investment. The time needed to return the investment is known as the payback period [48,49] and was calculated in Equation (4):

$$\text{Payback period} = \frac{\text{Cost of investment}}{\text{Annual cash flow}} \quad (4)$$

To calculate the minimum lactic acid selling price (MLSP, EUR·kg^{-1}) necessary to achieve a net present value of zero with an internal rate of return after taxes of 8%, a discounted cash flow rate of the return analysis was used. The operating cost per unit of the end product was the net production cost (EUR·kg^{-1}).

Estimates of the capital cost, operating cost, and revenue generation were used to analyze the economic performance of the process, which was then subjected to profitability, cash flow, and sensitivity assessments for the evaluation and comparison. Amortization criteria were stablished according to Agencia Tributaria [48].

While the net profit accounted for income tax (25%) [49], the gross profit measured the profitability by deducting the annual revenue from the annual operating costs. Finally, the ROI indicated the rate of the cash return over the plant lifetime without taking the cash discount into account. The ROI was defined in Equation (5):

$$\mathrm{ROI}\ (\%) = \frac{\text{Annual net profit}}{\text{Capital cost}} \cdot 100\% \quad (5)$$

Calculating the cumulative cash flow for each year served to demonstrate the cash flow trends that occurred over the plant's existence. To examine the impact on profitability, several discount rates were used, and the IRR was discovered when the final cash value was zero.

The working capital costs and fixed capital investment (FCI) costs were added to determine the overall capital cost. The FCI represented the costs associated with building the facility, including the price of purchasing the equipment, installation, piping, and other associated costs. The solid–fluid processing plant-delivered equipment cost as a percentage was assessed according to Peters et al. [43]. The NREL study [9] and Aspen Plus database were used to determine the equipment cost [50]. When data for this report were not accessible, either the built-in module in Aspen Plus or Peters et al.'s [43] data were used.

The installation cost was calculated from the equipment purchase cost using the proper multiplication factors that were listed in the literature [24,43]. The installation cost was equipment-specific. The costs of initializing the plant during the startup phase, such as the costs of procuring raw materials, utilities, and equipment testing, were covered by the working capital, which was projected to be 5% of the FCI [43]. Additionally, it was assumed that after the plant's existence, no additional capital expenses or revenue from the resale of the plant's facilities would be produced.

The overall variable production costs, fixed charges, plant overhead costs, and general expenses were all included in the predicted overheads. The raw materials cost was obtained from the current local market and [20–22]. The cost of chemicals was obtained from existing producers and the literature. The Ulrich technique [51] and process knowledge were used to estimate the labor requirements, with 40 h of work per week each shift. The utilities usage and costs were determined using Aspen Plus software and authors' process knowledge. According to municipal regulations, the costs of treating solid waste and wastewater were paid [52]. Logistic costs were calculated from the market and [30]. The straight-line method was used to determine the FCI depreciation during a 20-year lifetime with minimal salvage values [53].

The revenue was generated from the sales of products and energy. The current market prices of 80% lactic acid were defined according to [20,54], with a selling price of 1.5 EUR per kg.

2.5. Sensitivity Analysis and Break-Even Point

For this study, a sensitivity analysis was performed to determine the influential variability. The sensitivity analysis was performed because theoretical estimates on an industrial scale might not be accurate in various circumstances. The projection could change, and, in this situation, the sensitivity analysis would usually identify the possibilities that would be most likely to occur.

The sensitivity analysis was used to assess the effects of various factors on the economic performance. A number of variables were individually assessed and set at 50% variance at the beginning of the entire plant's lifetime because the global economic situation could change throughout the course of a plant's existence. These included the cow manure price, labor cost, utilities prices, financial expenses, taxes, variable costs, and yield. At an 8% discount rate, the NPV served as an indicator [55].

The amount of sales needed for income to equal costs is known as the break-even point. As long as the income kept rising, profits would continue increasing, calculated using future earnings. Equation (6) was used to determine the break-even point in units:

$$\text{Break} - \text{even point (in units)} = \frac{\text{Fixed costs}}{\text{Sales price per unit} - \text{variable cost per unit}} \quad (6)$$

3. Results and Discussion

3.1. Mass Balance

One hundred kt of LA overall per year was generated through fermentation for scenario I. It should be highlighted that just the lignocellulosic portion of the cow manure was utilized for the production of LA. The lignocellulose material represented 51.5% (w/w) of the dried cow manure, but the remaining components, which included protein, lipids, and carbohydrates, generated byproduct streams, were left out of the economic analysis. The modern maize-based manufacturing sector in LA also found certain byproduct streams, including corn germ, heavy steep water, and corn gluten feed and meal. To transform them into food, feed, energy, and materials for the purpose of waste treatment and economic return, the result included 11 subprocesses [56]. Byproduct utilization and commercialization need to be studied.

According to conventional calcium lactate precipitation and acidification with H_2SO_4, it was reported that 92% of the LA was recovered; however, any potential loss during the

adsorption due to activated carbon was not addressed [57]. Cow manure balances per process step are detailed in Table 4. The raw material input according to each scenario detailing the quantity of LA achieved taking into account the yield of each step was described.

Table 4. Annual cow manure mass balance per process step.

Parameter	Scenario I	Scenario II	Scenario III
Step	Quantity (t)	Quantity (t)	Quantity (t)
Raw material	1,579,328	789,664	315,866
Dry raw material	758,077	379,039	151,615
Fermented LA	109,723	54,861	21,945
LA recovered (92%)	100,945	60,567	20,189

3.2. Capital Cost

Table 5 shows the capital costs, which included both the fixed capital investment and working capital. In addition to the cost of the bare equipment, further expenses for constructing the plant were projected and included. The current literature was used to determine the related percentage of each item cost contribution to the FCI [43]. The working capital, which was projected to be 5% of the FCI, was intended to pay for the start-up costs for the plant, including the acquisition of raw materials, the testing of equipment, and the training of laborers. Scenarios II and III were calculated according to Equation (1).

Table 5. Total project investment summary for all scenarios.

Process Area	Percentage	Installation Factor Average	Scenario I Installed Cost (EUR)	Scenario II Installed Cost (EUR)	Scenario III Installed Cost (EUR)
A1: Feedstock handling	NA	1.7	12,095,436	7,980,012	4,605,105
A2: Pretreatment	NA	1.9	12,821,690	8,459,160	4,881,612
A3: SSAF	NA	1.9	7,846,272	5,176,609	2,987,317
A4: Enzyme production	NA	1.9	17,990,074	11,869,022	6,849,375
A5: Recovery	NA	2.2	19,000,203	12,535,459	7,233,962
A6: Wastewater	NA	1	17,820,506	11,757,150	6,784,815
A7: Storage	NA	2.1	3,637,493	2,399,850	1,384,906
A8: Boiler	NA	2.1	17,220,927	11,361,575	6,556,537
A9: Utilities	NA	2.2	474,476	313,037	180,648
Totals			108,907,077	71,851,875	41,464,277
Warehouse	4.00%	of inside battery limits (ISBL)	4,356,283	2,874,075	1,658,571
Site development	9.00%	of ISBL	9,801,637	6,466,669	3,731,785
Additional piping	4.50%	of ISBL	4,900,818	3,233,334	1,865,892
Total direct costs (TDC)			127,965,815.63	84,425,953.02	48,720,525.79
Proratable expenses	10.00%	of TDC	10,890,708	7,185,187	4,146,428
Field expenses	10.00%	of TDC	10,890,708	7,185,187	4,146,428
Home office and construction fee	20.00%	of TDC	21,781,415	14,370,375	8,292,855
Project contingency	10.00%	of TDC	10,890,708	7,185,187	4,146,428
Other costs (start-up, permits, etc.)	10.00%	of TDC	10,890,708	7,185,187.49	4,146,427.73

Table 5. *Cont.*

Process Area	Percentage	Installation Factor Average	Scenario I Installed Cost (EUR)	Scenario II Installed Cost (EUR)	Scenario III Installed Cost (EUR)
Total Indirect Costs			65,344,246	43,111,125	24,878,566
Fixed Capital Investment (FCI)			193,310,062	127,537,078	73,599,092
Working capital	5.00%	of FCI	9,665,503	6,376,854	3,679,955
Total Capital Investment (TCI)			202,975,565	133,913,932	77,279,047

The machinery prices were updated when required, according the total project investment (TPI), based on [58]. The factored technique, in which multipliers were added to the cost of the purchased equipment, was used. Such factored approaches for typical chemical processes have been described in many engineering texts [44,45].

According to a number of technoeconomic research works on bioconversion procedures [59,60], the fermenter is the piece of equipment that is reported to be the most expensive overall, which was quoted for more than eight million EUR in scenario I. The recovery area represented the biggest budget of the TDC, followed by the enzyme production, wastewater treatment, and boiler equipment. The smallest investment was for the utilities, followed by storage. The home office and construction fee was the biggest budget for indirect costs.

3.3. Operation Cost

Operation costs, such as variable and fixed costs, were analyzed. The raw supplies, waste management fees, and byproduct credits were examples of variable operating costs that were only incurred when the process was running. The Aspen Plus material balance was used to calculate the quantities of the raw materials consumed and waste created. The material balance calculations were conducted using Aspen Plus [9] as a reference and, when needed, were adapted to LA requirements through Excel calculations. The variable operating costs are summarized in Table 6. The $kg \cdot h^{-1}$ decreased from scenario I to the other two, the same as the feedstock processed. The biggest cost was glucose, followed by the raw material (cow manure) and ammonia. The electricity was close to 15% of the total cost.

Regardless of whether the plant was working at full capacity or not, the fixed operational costs were typically incurred in full. These expenses covered labor as well as numerous overhead charges. Numerous fixed operational cost hypotheses were based on Peters et al. [43]. The fixed operating costs were calculated according to the plant's needs by taking into account the expected level of automation for each area and adding a suitable amount of management and support staff, after which the number of employees was calculated. Salaries were calculated using both vacant positions listed on online job sites [61] and commercially available salary estimators [40]. A summary is shown in Table 7. A plant manager was needed in scenarios I and II; meanwhile, in scenario III, the plant engineer would manage those tasks. The same would apply for the laboratory manager; in this case, there would be a technician who would be in charge for scenario III. Technicians and workers (including shift supervisors) were dimensioned, taking into account that scenario I had three shifts per day, two for scenario II, and one shift for scenario III.

Table 6. Variable operating costs for the three scenarios.

			Scenario I			Scenario II			Scenario III		
Process Area	**Stream Description**	**Cost (EUR·t^{-1})**	**Usage (kg·h^{-1})**	**EUR/h (2023)**	**MEUR/y (2023 EUR)**	**Usage (kg·h^{-1})**	**EUR/h (2023)**	**MEUR/y (2023 EUR)**	**Usage (kg·h^{-1})**	**EUR/h (2023)**	**MEUR/y (2023 EUR)**
					Raw materials						
A1	Feedstock (wet)	56.92	104,167	520.84	4.41	68,725	343.62	2.91	39,659.58	198.30	1.68
A2	Sulfuric acid, 93%	98.99	1981	196.09	1.66	1307	129.37	1.09	754.23	74.66	0.63
	Ammonia	494.94	1051	520.18	4.40	693	343.19	2.90	400.15	198.05	1.68
A3	Corn steep liquor	62.69	1158	72.60	0.61	764	47.90	0.41	440.89	27.64	0.23
	Diammonium phosphate	1088.88	142	154.62	1.31	93.69	102.01	0.86	54.06	58.87	0.50
	Sorbitol	1242.86	44	54.69	0.5	29.03	36.08	0.3	16.75	20.82	0.2
A4	Glucose	640.35	2418	1548.36	13.1	1595	1021.54	8.6	920.61	589.51	5.0
	Corn steep liquor	62.69	164	10.28	0.1	108.1996	6.78	0.1	62.44	3.91	0.03
	Ammonia	494.94	115	56.92	0.5	75.87	37.55	0.3	43.78	21.67	0.2
	Host nutrients	906.43	67	60.73	0.5	44.20	40.07	0.3	25.51	23.12	0.2
	Sulfur dioxide	335.30	16	5.36	0.045	10.56	3.54	0.03	6.09	2.04	0.02
A5	Methanol	191.55	15	2.87	0.02	9.90	1.90	0.02	5.71	1.094	0.01
A6	Caustic	164.98	2252	371.53	3.1	1485.77	245.12	2.1	857.41	141.45	1.2
A8	Boiler chems	5511.98	1	5.51	0.0	0.66	3.64	0.0	0.38	2.10	0.02
	FGD lime	219.97	895	196.88	1.7	590.48	129.89	1.1	340.75	74.96	0.6
A9	Cooling tower chems	3303.29	2	6.61	0.1	1.32	4.36	0.04	0.76	2.52	0.02
	Makeup water	0.28	147,140	41.16	0.3	97,076.20	27.15	0.2	56,020.73	15.67	0.1
	Subtotal			3825.23	32.4		2523.71	21.4		1456.38	12.3
					Waste disposal						
A8	Disposal of ash		5725	200.94	1.70	3777	132.57	1.12	77	2.69	0.02
	Subtotal			200.94	1.70		132.57	1.12		2.69	0.02
					Byproducts and credits						
	Grid electricity (KW)		12,797	639.85	5.41	8443	422.14	3.57	4872	243.61	2.06
	Area 100 electricity		859	42.95	0.36	567	28.34	0.24	327	16.35	0.14
	Subtotal			682.8	5.776		450.480	3.811		259.963	2.20
	Total variable operating costs			4708.97	39.84		3106.76	26.28		1719.03	14.54

One of the most challenging parts of running a business is managing the payroll. Therefore, it was important to balance it, having the right number of personnel to maximize sales whilst avoiding overstaffing. The number of positions varied from scenario I to II and III, as the raw materials processed needed one, two, or three shifts per day. The management positions were dimensioned according to this. There are several ways to determine an ideal company payroll balance, but one of the best and most popular approaches is to try to maintain a payroll close to a set percentage of gross revenues. The payroll was 11.9%, 16.3%, and 33% of the gross revenue for scenarios I, II, and III, respectively. Scenario I and II values were between the recommended range for the chemical industry [62]. However, scenario III's payroll had too much weight on the revenue.

Table 7. Fixed operating costs for the three scenarios.

Labor and Supervision							
		Scenario I		**Scenario II**		**Scenario III**	
Position	Salary (EUR)	Positions	Total cost (EUR)	Positions	Total cost (EUR)	Positions	Total cost (EUR)
Plant manager	141,569	1	141,569	1	141,569	0	0
Plant engineer	67,414	2	134,828	1	67,414	1	67,414
Maintenance supervisor	54,894	1	54,894	1	54,894	1	54,894
Maintenance technician	38,522	12	462,264	8	308,176	4	154,088
Lab manager	53,931	1	53,931	1	53,931	0	0
Lab technician	38,522	2	77,044	2	77,044	1	38,522
Lab tech-enzyme	38,771	2	77,542	1	38,771	1	38,771
Shift supervisor	46,227	4	184,908	2	92,454	1	46,227
Shift operators	38,522	20	770,440	8	308,176	4	154,088
Shift open-enzyme	38,771	8	310,168	4	155,084	3	116,313
Yard employees	26,966	4	107,864	3	80,898	2	53,932
Clerks and secretaries	34,670	3	104,010 EUR	2	69,340	1	34,670
Total salaries (EUR)			2,479,462		1,447,751		758,919
Labor burden (90%) (EUR)			2,231,516		1,302,976		683,027
Other overhead							
Maintenance of ISBL (%)	3.00		3,838,974		2,532,779		1,461,616
Property insurance of FCI (%)	0.70		1,420,829		937,398		540,953
Total fixed operating costs (EUR)			7,739,265		4,917,927		2,761,488

3.4. Revenue and Profitability Analysis

The second year, the revenue was 33,820,690 EUR for scenario I. LA sales were 95% of the total income; meanwhile, byproduct sales were only 5%. A profitability study was performed to measure and evaluate the ability of the plant to generate a profit. Table 8 summarizes the executive data for the three scenarios. The NPV was positive for all the scenarios, and the IRR was bigger than the interest rate. The NPV of scenario III was small compared with the other two, being the same for the IRR, which was 26% for scenario I and only 12% for scenario III. This was translated into the payback time, which was 3, 4, and 8 years for scenarios I, II, and II, respectively, less than the plant's 20-year lifetime. The calculated ROI for scenario I was 16.7%, a positive value, which also meant the project was viable. After finishing the amortization, the ROI increased to 24.1%. The ROI decreased as the volume of the plant decreased. Scenarios II and III had a ROI of 9.94% and a 3.42%, respectively. As the ROI should have been above 10% to be acceptable [63], only scenario I fulfilled this requirement.

The minimum lactic acid selling price (MLSP) was 0.945 EUR·kg^{-1} for scenario I, which, compared to the minimum ethanol selling price (MESP) of 0.68 EUR·kg^{-1} ($2.15 per gal) from the same process flowsheet [9], was 30% more expensive. The MLSP was anticipated to decrease furthe due to future yield improvements and a cow manure price reduction. According to the literature, the cost of producing 70% (*w*/*w*) LA from wheat flour was approximately 0.7933 EUR·kg^{-1} [39], the cost of producing 50% (*w*/*w*) LA at food grade from ultrafiltered whey was 1.19 EUR·kg^{-1} [64], the cost of producing 80% (*w*/*w*) lactic acid from sugarcane juice was 3 EUR·kg^{-1} [65], and the cost of producing LA from corn stover was 0.50 EUR·kg^{-1} [66]. Then, a cost of producing LA from cow manure of 0.945 EUR·kg^{-1} would be competitive and comparable to that of producing LA from food

crops and corn stover. The MLSP increased as the volume of the plant decreased. Scenarios II and III achieved a higher MLSP, with 1.070 and 1.289 EUR·kg^{-1}, respectively.

Table 8. Executive summary of cow manure as feedstock for the production of lactic acid.

Parameter	Scenario I	Scenario II	Scenario III
Cow manure plant capacity (t·year^{-1})	1,579,328	789,664	315,866
Design on-stream factor (346 days·year^{-1})		0.95	
Feedstock		Cow manure	
Feedstock price (EUR·t^{-1})		5	
Main products		Lactic Acid	
Selling price (EUR·kg^{-1})		1.5	
Total capital investment (MEUR)	202.98	133.91	77.28
Operation cost (MEUR·year^{-1})	50.85	25.40	10.17
Revenues (MEUR/year) after amortization	48.85	23.20	8.30
LA batch size (t)	553.1	276.6	110.6
Yield (%)		33.3	
OEE (%)		85	
Unit production cost (EUR·kg^{-1})	0.748	0.809	0.924
Payback time (years)	3	4	8
IRR (After Taxes)	26%	20%	12%
NPV (at 8% Interest) (MEUR)	320	125	24
ROI (%)	16.66	9.94	3.42
MSP (EUR·kg^{-1})	0.945	1.070	1.289
20 t daily trucks (365 days)	104	52	21

The unit production cost increased from scenario I to III, as the size plant was smaller. Finally, to provide an indicator of the plant's size, a number of 20 t trucks to receive the raw material was calculated. Scenario I needed 104 trucks per day, 52 for scenario II, and 21 for scenario III. This required more than 100 daily trucks to operate the plant at 100% capacity.

As shown in Figure 7, the discount rate was a crucial instrument for adjusting future cash flows to the present value. The discount rate was the interest rate used to find the present value of future cash flows. By raising the discount rate, which, in turn, indicated how much risk or uncertainty the investment could withstand, the quality of the investment could be shown. The results showed that the project discount rate was 8%, making it economically viable. Decreasing the discount rate would increase the project revenue, while increasing it would reduce the benefit. The project was simulated at a 1% rate up to 20% when the NPV was close to zero. The NPV was zero for scenario I, when the discount rate was 26%.

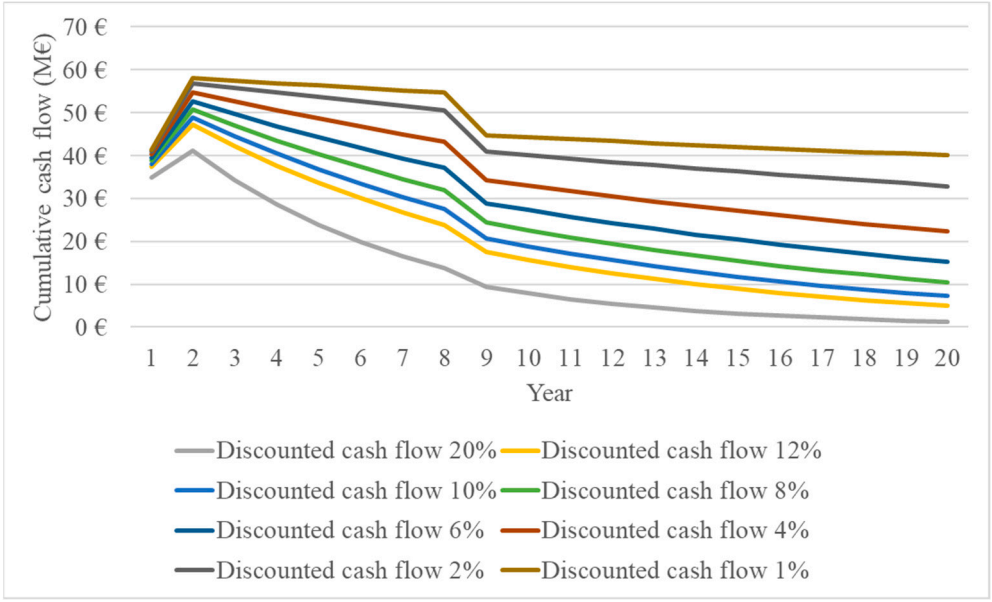


Figure 7. Cumulative cash flow at several discount rates for scenario I.

3.5. Sensitivity Analysis and Break-Even Point

The sensitivity factors for this study were ±25% variations in the cost cow manure price, labor cost, utilities price, financial expenses, taxes, variable costs, and yield. Since the factory was built to last 20 years, changes in the labor market and economy were expected and could likely pose a risk to the plant's economics. A sensitivity analysis was needed to check which variables had more impact. As shown in Figure 8, the variable with higher impact was yield. Increasing the yield could have a possible impact on the sales quantity due to the quantity of the available product and production costs. As the yield was studied at a laboratory scale [12], its value was already demonstrated. Meanwhile both variables for sales depended on the market, which was quite stable and a growing sector [67]. The yield had a bigger impact in scenario II out of all three. The second variable in terms of impact was the utilities price; the smaller the plant, the bigger the impact. Scenario III was more sensitive to utility price changes than scenario I. Financial expenses was the third variable with more impact, and the effect was similar for all scenarios. Scenario I was more sensitive to labor costs, as there were more factory workers. The same applied to variable costs. The impact of cow manure was similar for all three scenarios, and was the fourth variable in terms of impact.

A summary of all variable percentage variations is shown in Table 9, which was the NPV fluctuation between a ±25% parameter variation. The yield varied 516% in scenario I and was higher in scenario II. Meanwhile, from scenarios II to III, there was a decrease in the yield impact due to the negative NPV for −25% of the value, and a modest NPV value for +25% yield variation in scenario III. The financial expenses were the variable with the lowest impact (99 to 100%); meanwhile, the variable costs, taxes, and labor costs had a bigger impact. The sensitivity of the factors increased as the plant size decreased.

The cow manure price depended on the availability and agricultural needs, which was variable, so the value in which the NPV would be zero was calculated next. The cow manure price would have to increase 1500% in order to have a negative NPV value, which meant the plant would be operative according to the current market or with price increases below this value. For scenario II, the increase had to be 1150%, while for scenario III, the cow manure price would have to increase 550% to have a negative NPV. The tendency is shown in Figure 9.

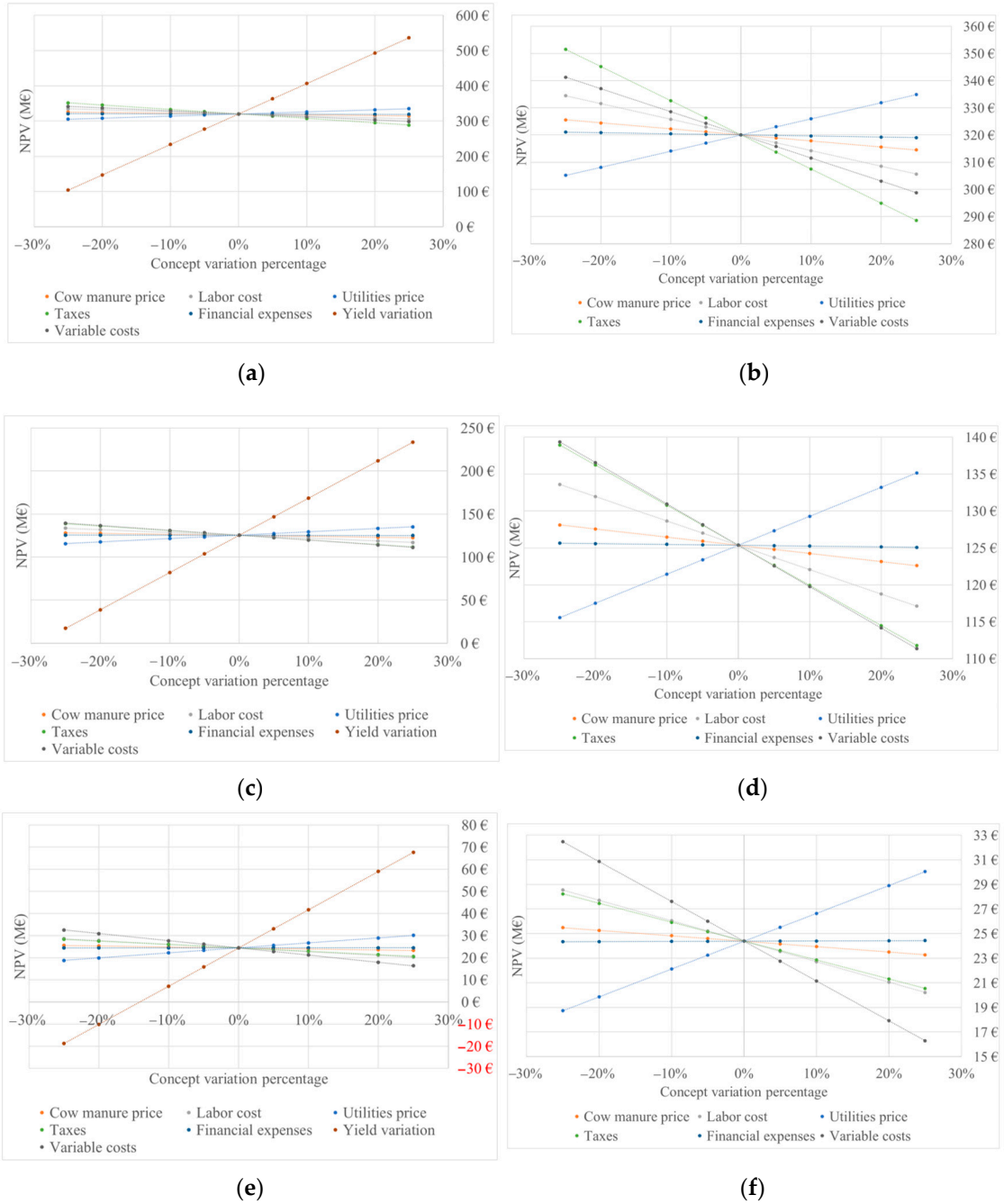


Figure 8. Sensitivity analysis for different variables against NPV results. (**a**) Scenario I for all variables including yield. (**b**) Scenario I for all variables except yield. (**c**) Scenario II for all variables including yield. (**d**) Scenario II for all variables except yield. (**e**) Scenario III for all variables including yield. (**f**) Scenario III for all variables except yield.

The break-even value is shown in Figure 10, indicating that the plant should have been operated at a rate and time that were at least as high as those necessary to create a gross profit. Accordingly, for scenario I, the factory would have to sell at least 23,150 t of lactic acid annually. Taking into account that this was a 23% of the total plant's capacity, collecting enough feedstock to produce it would be feasible. The break-even point was lower for the other two scenarios. Scenario II needed to sell 14,250 t of LA, and scenario II required 8020 t of LA.

Table 9. Sensitivity variables percentage variation.

	Scenario I	**Scenario II**	**Scenario III**
Variable	Variation	Variation	Variation
Cow manure price	97%	96%	91%
Labor cost	91%	88%	71%
Utilities price	110%	117%	160%
Taxes	82%	80%	73%
Financial expenses	99%	100%	100%
Yield variation	516%	1347%	447%
Variable costs	88%	80%	50%

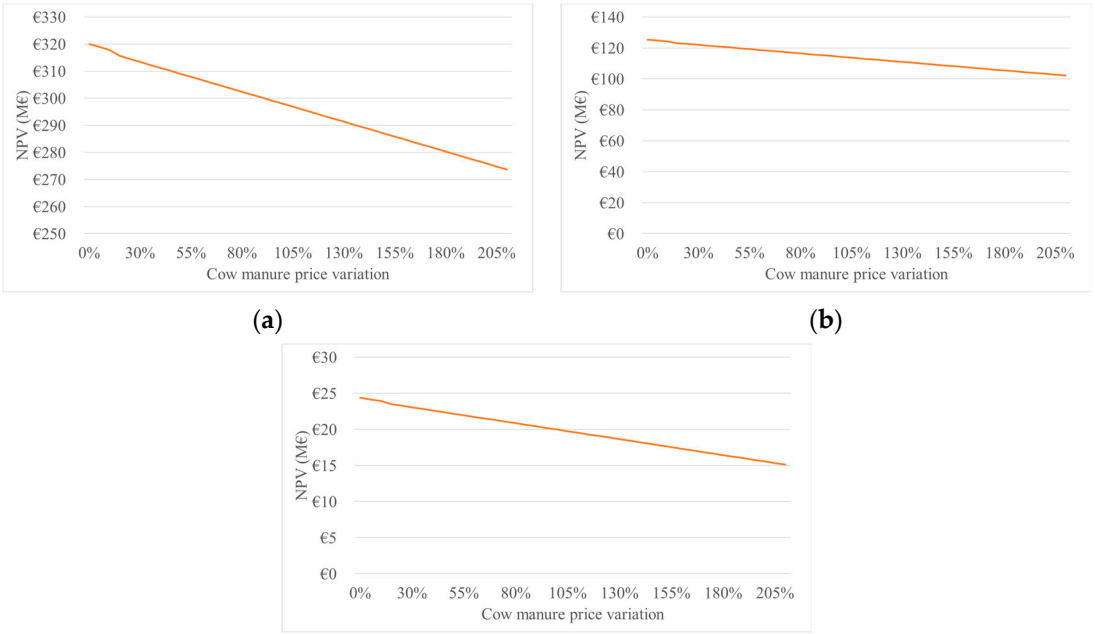


Figure 9. Cow manure price variation impact in NPV (EUR). (**a**) Scenario I, (**b**) scenario II, and (**c**) scenario III.

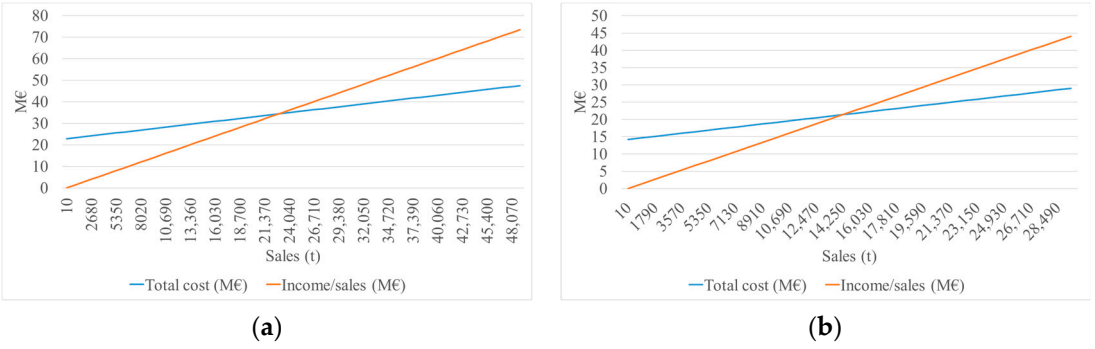
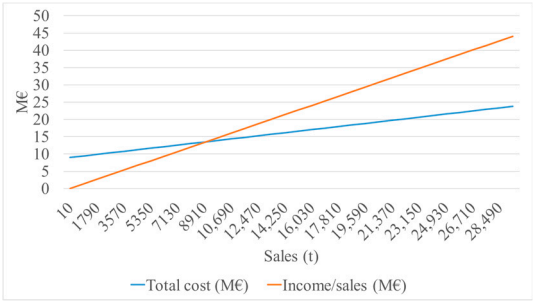


Figure 10. *Cont*.



(**c**)

Figure 10. Break-even chart for sales in EUR. (**a**) Break-even chart for scenario I; (**b**) break-even chart for scenario II; (**c**) break-even chart for scenario III.

A serial LA plant using cow manure was assessed and revised in this study to evaluate its feasibility in order to improve cow manure waste management, transforming it into a value-added product. Strong points of this study included it demonstrating the economic viability of the process and the yield as a variable with more impact on the NPV. Nevertheless, this process showed some weaknesses in terms of scale; it needed a certain volume to be feasible, and this increased the difficulty to achieve and manage the raw material.

4. Conclusions

This study demonstrated the technoeconomic assessment of a biorefinery based on cow manure waste that produces lactic acid. Three scenarios were analyzed, modifying the size of the plant. The technoeconomic study revealed that the minimum lactic acid selling price for scenario I was 0.945 EUR per kg, which was comparable to other research articles. Scenarios II and III achieved a bigger MLSP (1.070, and 1.289 EUR·kg^{-1}, respectively), which meant that increasing the plant size increased the profitability.

The study hypotheses were all economically plausible for all scenarios. The IRR, payback time, and net NPV were the main considerations during the economic analysis. Scenario I had the best economic indicators; the NPV achieved at an 8% discount rate was positive, with a 353,487,680 EUR value; the IRR was positive; and the project was feasible up to a 26% discount rate. The calculated payback time was three years, which was lower than the plant's lifetime. The ROI was also positive, with a return of 16.7%, and the break-even point was 21% of the total capacity. On the other hand, scenarios II and III were also feasible, but decreasing the profitability as the plant size decreased; the ROI of these both scenarios was below 10%.

Results from the sensitivity analysis for scenario I revealed that the critical point was the yield variation, which was translated directly into more or less production, as well as sales capacity and costs. On the other hand, the cow manure price, labor cost, and variable cost results were not so significant. There was a big margin in terms of the cow manure price, as it could increase up to 1500% (scenario I) in order to reach a negative NPV. As the plant size decreased, the sensitivity increased. Scenario III was the most sensitive of all three to variable modifications. byproduct utilization and commercialization need to be studied in order to increase the plant's competitiveness. The process studied and presented in this paper was a sustainable technology with competitive economic performance that recycled the lignocellulosic portion in cow manure. As a result, it would support the switch from the current linear to a circular bioeconomy. The process demonstration at the pilot size is planned to be the main focus of future research to validate the model and analytics, since the cost of producing lactic acid from cow manure is competitive and comparable to that of producing LA from food crops and corn stover.

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