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(RESEARCH ARTICLE)

Economic evaluation of citric acid production from molasses using SuperPro designer: A process simulation approach

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Abstract

This study presents a techno-economic evaluation of citric acid production from molasses, by *Aspergillus niger*, modeled and analyzed through SuperPro Designer software. The process simulation included fermentation, solvent extraction, crystallization, and waste treatment, forming a complete industrial production cycle. Capital and operating costs were estimated using built-in costing tools, incorporating international benchmarks for raw materials prices, labor, utilities and equipment. Economic evaluation showed noteworthy results as the process is deemed viable and economically feasible according to the Economy Evaluation Report. The total capital investment was estimated at 110.06 million USD, with fixed capital accounting for 84% of the total. Annual production was projected at 60.6 million kg of citric acid, generating revenues of approximately 90.89 million USD against annual operating costs of 71.82 million USD. The resulting net profit of 12.4 million USD yields a payback period of 8.9 years and a return on investment (ROI) of 11.2%. Results found in this paper demonstrated the potential of using SuperPro Designer® as a simulation tool in estimating costs and predicting the process feasibility. The analysis confirmed that the process is capital-intensive but economically sustainable, especially at large-scale production. These findings support the potential implementation of the proposed citric acid production facility in an industrial context.

Keywords: Citric Acid; *Aspergillus niger*; Molasses; Process Simulation; SuperPro Designer; Techno-Economic Analysis

1. Introduction

Citric acid is one of the most important organic acids produced in a fermentation process. Because citric acid is so expensive and the market is so competitive, profit margins are small. Every year, over 1.1 million tons are produced worldwide. The majority of production is accomplished with strains of *Aspergillus niger* that use cane or beet molasses as a substrate. (Taras, and Woinaroschy, 2012). Citric acid is a prospective value-added chemical that may be made from biomass and is utilized in food, medicine, drinks, and agriculture. Seventy percent of the citric acid produced is utilized to improve the flavor of food and drink, with the remaining portion being used to complex metals, buffers, and antioxidants (Wang, et al, 2020). Microbial fermentation or extraction from a variety of natural sources, including lime, lemon, and orange, can be used to manufacture citric acid. On the other hand, most plants cannot produce enough to meet market demands. As a result, several bacteria are being used to produce citric acid on a big scale. (Latif, et al, 2025). Techno-economic evaluation is crucial in this context, not only for determining the financial viability of production facilities but also for directing process design choices and enhancing cost-efficiency through fermentation, primarily employing *Aspergillus niger*, under strictly regulated biochemical and environmental conditions. (Towler and Sinnott, 2013). Techno-economic evaluation is essential to the design and optimization of industrial fermentation processes

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because of the growing demand for citric acid and the significance of sustainable and profitable production techniques. (Show et al., 2015; Towler and Sinnott, 2013). Process conditions and techno-economic analysis are the main elements that directly support the commercialization of more environmentally friendly, sustainable technologies. A techno-economic analysis can be performed to estimate the total cost of sustainable technology. It is also possible to critically analyze feedstock, operation mode, and utility expenses. (Bharathiraja, et al, 2022). SuperPro Designer® is a software program utilized in a variety of industries, including food processing, consumer goods, and bioprocesses. It helps with process modeling and project economic analysis while optimizing integrated processes in the biotechnological field. (Diniza, et al, 2024). Software called SuperPro Designer® can be used to perform techno-economic calculations in process engineering. Software can be used to simulate processes, including continuous and batch processes. In addition, there are databases covering chemicals, equipment, and economic data. (Bergman, 2016). This study presents a comprehensive economic evaluation of citric acid production through microbial fermentation using *Aspergillus niger*, with process simulation conducted in SuperPro Designer. The objective is to quantify the capital and operating costs, estimate profitability indicators, and assess the industrial feasibility of the process configuration under realistic assumptions.

2. Materials and Methods

2.1. Materials

The following raw materials (Molasses and nutrient) were used in the process design for citric acid production from cane molasses using *Aspergillus niger*: The molasses is diluted and sterilized in a media preparation unit to remove contaminants. Nutrients such as nitrogen, phosphate, and trace elements are added to optimize microbial growth.

2.2. Equipment

This investigation will be conducted using a personal computer for simulation purposes using SuperPro Designer Software (Version 4.53)

2.3. Methods

The research methodology followed in this study was based on the computational process simulation tool, following the Figures (1), (2) and (3). Information related to industrial citric acid production processes, such as operating parameters, process variables and unit operation layouts, was collected from relevant literature and industrial case studies (Fritsche et al., 2025). A base case production scenario using *Aspergillus niger* and molasses as the primary feedstock was developed. Several alternative process configurations were also designed to explore optimization options across upstream fermentation and downstream recovery stages. SuperPro Designer Software (Version 4.53) was utilized as the primary simulation platform for modeling the process flow, performing mass and energy balances, and conducting a detailed techno-economic evaluation of each configuration. The software's built-in costing tools were employed to estimate capital and operating costs, including expenses related to raw materials, equipment, utilities, labor, and maintenance. In parallel, a set of key economic indicators, such as total capital investment (TCI), net profit, payback period and return on investment (ROI), were calculated to assess financial viability. The most promising configuration was identified based on a comprehensive comparison of economic performance, scalability, and operational efficiency. The software calculated the total capital investments and operating costs for the process. The results from this calculation are reflected in the Executive Summary for the project.

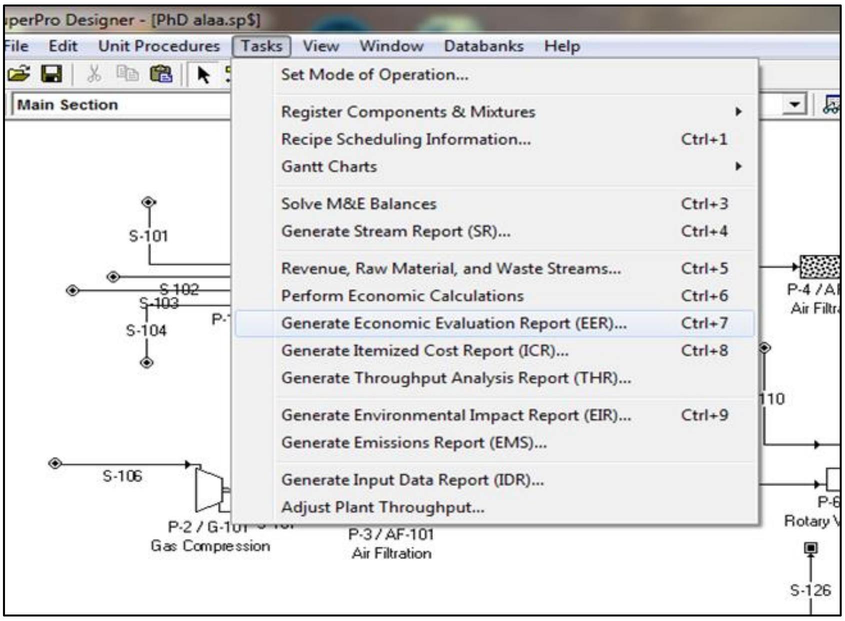

Figure 1 Reports dialog box

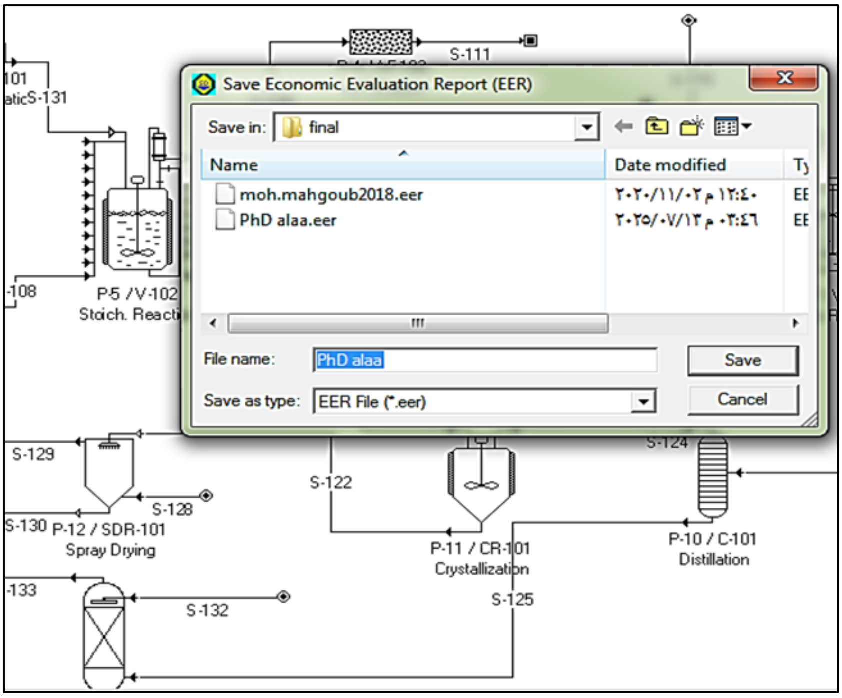

Figure 2 Save economic evaluation report

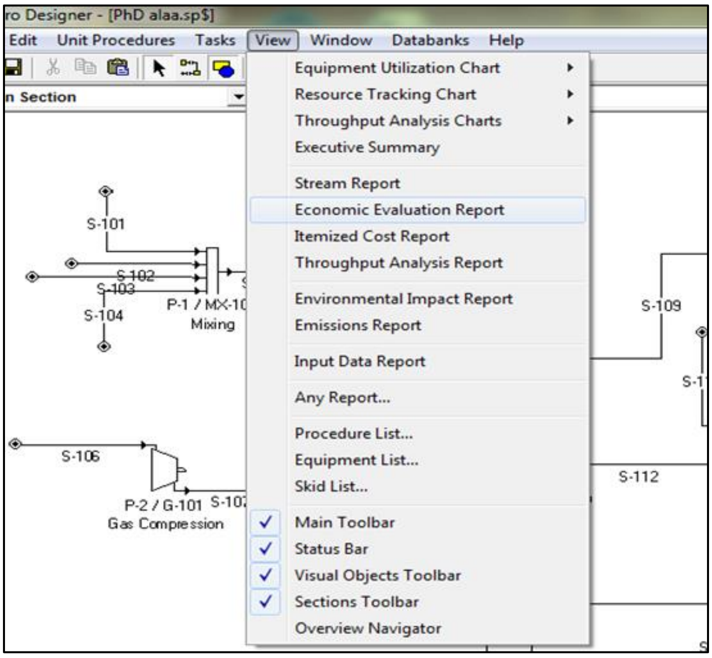

Figure 3 View of the Reports

2.3.1. Estimation of Total Capital Investment:

The total capital investment for the proposed plant is estimated as following:

2.3.2. Total Capital Investment (TCI):

- The total capital investment for the proposed plant is estimated:
- TCI = Fixed Capital Investment + Working Capital Investment……………………………………………………(1)
- Fixed Capital Investment (FCI) = Direct Costs + indirect costs……………………………………………………(2)

2.3.3. Working Capital Investment (WCI):

Working Capital Investments (10_ 20)% of FCI ……………………………………………………………………………………(3)

2.3.4. Annual Revenue:

Revenue = Market selling price * annual production of citric acid………………………………………………………(4)

2.3.5. Annual Operating Costs:

Based on realistic estimations from SuperPro Designer and industrial data, the total operating costs can be accurately calculated.

2.3.6. Profitability Indicators:

Gross Profit = Revenue – Operating Costs ……………………………………………………………………………………………(5)

2.3.7. Payback Period Calculation:

- The Payback Period is the time needed to recover the initial investment from net profits.
- Payback Period= Total Investment / Net Profit ……………………………………………………………………………(6)

2.3.8. The Return on Investment (ROI):

ROI = Net profit / TCI * 100……(7)

3. Results and discussions

The following table (1), shows the major equipment specification and there costs using SuperPro Designer Software (Version 4.53)

Table 1 The major equipment specification and cost (2025 Prices)

Equipment ID	Equipment Description	Quantity	Unit Cost ($)	Total Cost ($)
MX-101	Mixer	1	0	0
G-101	CF Compressor	1	1,500,000	1,500,000
AF-101	Air Filter	1	42,000	42,000
V-102	Stirred Jacket Vessel	22	1,062,000	23,364,000
AF-102	Air Filter	3	71,000	213,000
RVF-101	Rotary Vacuum Filter	6	319,000	1,914,000
V-101	Stirred Jacket Vessel	12	1,062,000	12,744,000
BCF-101	Basket Centrifuge	2	490,000	980,000
MSX-101	Mixer-Settler Extractor	1	9,000	9,000
C-101	Distillation Column	1	278,000	278,000
CR-101	Crystallizer	1	553,000	553,000
SDR-101	Spray Dryer	1	173,000	173,000
ST-101	Heat Sterilizer	1	1,126,000	1,126,000
C-102	Absorber	1	212,000	212,000
—	Cost of Unlisted Equipment	—	—	10,778,000
Total Equipment Purchase Cost				**53,890,000**

Table (1) shows that the total equipment purchase cost amounted to 53.89 million USD. The stirred jacket vessels accounted for the largest portion of the investment, highlighting the central role of the fermentation stage in citric acid production. Significant costs were also allocated to filtration and separation units, such as vacuum filters and centrifuges, which are essential for product recovery. Additional investment was made in extraction, crystallization, drying, and sterilization units, indicating a complete and integrated production line. Notably, a separate cost of 10.78 million USD was assigned to unlisted equipment, likely covering auxiliary and support units. This distribution reflects a well-structured and industrially efficient process design.

The direct capital costs represent the physical and infrastructural components required to establish the citric acid production facility, shown in (Table 2).

Table 2 The direct costs (2025 Prices)

Item	% of FCI	Cost (USD)
Process Equipment	40%	53,890,000
Instrumentation and Control	9%	5,978,448
Piping and Connections	3.3%	2,192,098
Electrical Systems	4%	2,657,088
Buildings and Services	6%	3,985,632
Site Development	1.5%	996,408
Utilities	8%	5,314,176
Land	1.5%	996,408
Total		76,010,558

As shown in the table (2) process equipment constitutes the largest portion (40%) of the fixed capital investment, which is justified due to the complexity of fermentation, extraction, and purification units. Instrumentation and control (9%) also hold a significant share, reflecting the need for precise environmental monitoring in biotechnological processes. Piping (3.3%) and electrical systems (4%) support the integration of all units, while buildings and site development (7.5% combined) ensure proper layout and operational space. Utilities (8%) are essential for steam, air, and cooling systems, which are heavily utilized in this process. Land costs are kept minimal (1.5%), assuming the plant is located in an industrial area. This cost structure aligns with standard designs for biochemical manufacturing, where equipment and utility systems dominate capital expenditure.

Table 3 Bellow, shows the indirect capital costs covers essential support activities for the successful completion and operation of the citric acid plant

Table 3 The indirect costs (2025 Prices)

Item	% of FCI	Cost (USD)
Engineering and Supervision	6.7%	4,451,622
Administrative Overhead	22%	14,614,464
Contingencies	1.5%	996,408
Emergency Funds	6%	3,985,632
Total		**24,048,126**

From table (3), engineering and supervision (6.7%) ensure proper design and commissioning, while administrative overhead (22%) is the largest expense, covering management and legal services. Contingencies (1.5%) provide a buffer for unforeseen costs, and emergency funds (6%) address unexpected risks. This cost distribution aligns with industry standards and supports project reliability.

To evaluate the financial feasibility of the process, the annual operating cost was estimated based on material consumption, utilities, labor, maintenance, and other overhead expenses. The following table (4) summarizes the breakdown of these costs

Table 4 The annual operating cost (2025 Prices)

Cost Item	Cost ($/Year)	Percentage (%)
Raw Materials	6,000	0.01
Labor-Dependent	1,778,000	2.48
Equipment-Dependent	68,966,000	96.03
Laboratory/QC/QA	267,000	0.37
Consumables	0	0.00
Waste Treatment/Disposal	0	0.00
Utilities	801,000	1.11
Transportation	0	0.00
Miscellaneous	0	0.00
Advertising and Selling	0	0.00
Running Royalties	0	0.00
Failed Product Disposal	0	0.00
Total	71,817,000	100.00

From table (4) the economic analysis showed that the total annual operating cost was approximately 71.82 million USD, with 96.03% attributed to equipment-dependent costs, indicating a highly automated process. Labor costs were minimal at 2.48%, and utilities accounted for 1.11%. No costs were reported for waste treatment, transportation, or consumables, suggesting they were negligible or included elsewhere. Overall, the process is capital-intensive but economically viable if production is maintained at a large scale.

The following table (4) shows the assess the overall economic performance of the process, key financial indicators was calculated based on the estimated investment, operating costs, and revenues. These indicators provide insight into the profitability and feasibility of the project.

Table 5 The summary of Key financial indicators

Indicator	**Value million USD**
Total Capital Investment	110,064,552.4
Fixed Capital Investment	100,058,684
Annual Operating Costs	71,817,000
Annual Revenue	90,894,000
Net Profit	12,400,050
Payback Period	8,9 years
ROI	11.2%

From table (5) the financial indicators summarized in the table confirm the economic feasibility of the proposed citric acid production plant. The total capital investment of USD 110.06 million with 84% allocated to fixed capital reflects a well-structured and realistic capital plan. With annual operating costs estimated at USD 71.82 million and annual revenue reaching USD 90.89 million, the plant achieves a net profit of approximately USD 12.40 million. This leads to a calculated payback period of 8.9 years, indicating a reasonable return horizon for a biochemical facility of this scale. The return on investment (ROI) of 11.2% suggests sustainable profitability and supports the project's financial viability over the long term.

4. Conclusion

The implementation of the proposed citric acid production process using SuperPro Designer software demonstrates strong economic potential, particularly for industrial applications in middle-income countries. The simulation-based evaluation provided a comprehensive insight into capital requirements, operating costs, and profitability indicator highlighting a net profit of 12.4 million USD per year, a payback period of 8.9 years, and a return on investment (ROI) of 11.2%. These figures confirm the viability and scalability of the design. Such process modeling tools serve as valuable decision-making aids in the optimization and industrial valorization of agro-industrial byproducts like molasses, contributing to more sustainable and economically attractive biotechnological production systems.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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