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Modelling and Simulation of Citric Acid Production from Molasses Using *Aspergillus Niger*

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Abstract

Citric acid is a widely used organic acid and an important intermediate in the tricarboxylic acid (TCA) cycle, where carbohydrates are oxidized to carbon dioxide. The objective of this study is to design and simulate an industrial process for citric acid production using molasses as a low-cost carbon source through fermentation by Aspergillus niger. Molasses samples, obtained from the Kenana Sugar Factory, Sudan, were analyzed in the laboratory to assess their chemical and physical properties, including sugar content, ash, and reducing sugars, to confirm their suitability as a fermentation substrate. The fermentation medium was formulated by supplementing molasses with essential nutrients such as urea, magnesium and calcium sulfates, vitamins, and legume soaking water as a natural phosphate source. The results of fermentation experiments were performed in 10-liter bioreactors under optimal conditions of 30 °C, pH 4.5, and 150 rpm, producing 38.5 g/L of citric acid after 7 days. For process scale-up, modeling, and optimization, SuperPro Designer® (Version 4.53) was used to simulate the entire production chain, including media preparation, fermentation, solvent extraction (MIBK), crystallization, and drying stages. The results showed that the mathematical model predicted a citric acid yield of 2063.6 kg per batch with an efficiency of 84.7%, while the process simulation achieved 7574.5 kg per batch under ideal conditions with 100% efficiency and a reduced fermentation time of 5 days. The solvent recovery efficiency was very high at 99.05%, indicating effective separation and reuse of MIBK. Overall, the study demonstrates that integrating experimental work with mathematical modeling and process simulation significantly improves process understanding and confirms that industrial-scale production of citric acid from molasses using Aspergillus niger is feasible, efficient, and environmentally sustainable.

Keywords: Aspergillus niger, Citric acid, Fermentation, MIBK extraction, Modelling and Simulation, Molasses.

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INTRODUCTION

Citric acid, a tricarboxylic acid with a molecular weight of 210.14 Da and a weak organic acid with the formula C6H8O7, functions as an intermediate product in the citric acid cycle. Citric acid is one of the most sought-after goods for ingestion worldwide due to its low toxicity. (Latif et al*.,* 2025). At the industrial level, citric acid is produced through solid-state fermentation or submerged fermentation, primarily facilitated by *A. niger*. As of right now, the most preferred method of producing citric acid using microbes is the submerged fermentation process used by *A. niger.* The filamentous fungus *A. niger* is employed extensively in a variety of industrial fermentation processes to produce a wide range of primary and secondary metabolites, including proteins, enzymes, and organic acids, particularly citric acid. (Latif et al., 2025). The first method of fermenting citric acid was surface cultures, and during the 20th century, several of commercial manufacturing plants were set up in Germany and England. (Abghari & Chen, 2017). Molasses is frequently fermented by microorganisms submerged in it to produce citric acid for commercial use. (Show et al., 2015). Fermentation with *Aspergillus niger* is the main process used worldwide to produce citric acid. (Auta et al., 2014). Citric acid is a versatile ingredient that is widely utilized in the food and beverage sector. Its main function in beverages such as fruit juices, energy drinks, and soft drinks is to balance sweetness and increase tartness by acting as an acidulant. As an antioxidant, it also inhibits lipid oxidation in items like processed meats and oils, and because of its chelating activity with metal ions like iron and copper, it helps prevent food spoilage and color degradation. Its preservation qualities give canned goods, sauces, jams, and fruit-based products a longer shelf life by reducing pH and preventing microbiological development. Additionally, as a buffering and emulsifying agent, citric acid enhances the texture and stability of dairy products, confections, and emulsions. (Yuan et al., 2022; Ding et al., 2023)**.** A suitable strain and the optimization of fermentation parameters are essential for a successful procedure. While a variety of microorganisms, including yeast, fungus, and bacteria, participate in the fermentation of citric acid. *Aspergillus niger* plays a significant part in the large-scale production of citric acid. (Khurshid et al., 2024). For the industrial manufacture of citric acid. *Aspergillus niger* is the ideal microbe. Due to its increased output yield. It ferments a wide range of cheap raw materials and yields high quantities, and is easy to work with. Commercial production-ready industrial strains of this microbe have been created through the use of mutagenesis and strain selection. *A. niger* has been transformed utilizing a range of mutagens, such as radiation from ultraviolet, X-ray, and gamma rays and compounds like ethyl methane sulphonate and diethyl sulphonate. (Fritsche et al., 2025). *Aspergillus niger* has a large number of advantages as compared to other microorganisms such as high capacity for citric acid accumulation, easy handling, high yield of citric acid, capability to process various substrates for fermentation and low fermentation cost (Latif et al., 2025). Molasses is one of the most economical forms of carbohydrates and is categorized as either beet or cane molasses depending on its origin. To accommodate the growing demand, large-scale fermentation has attracted a lot of interest. The biological process of fermentation produces carbon dioxide and ethanol as waste products from the conversion of carbohydrates like glucose, fructose and sucrose into cellular energy (Bukhari et al., 2022). The importance of dynamic mathematical models in analyzing complex processes is extremely significant and cannot be overstated. Dynamic modeling and process simulation contribute substantially to enhancing process economics, as well as improving design, operational efficiency, and control strategies**.** (Amenaghawon & Aisien, 2012). SuperPro Designer® is a sophisticated process simulation tool that is extensively utilized in the food, pharmaceutical, biotech and specialty chemical industries. It has large databases for chemicals, equipment, utilities and cost estimation, and it allows for thorough modeling of both batch and continuous processes (Carmichael & Petrides, 2020). The software facilitates thorough techno-economic analyses, equipment sizing, process scheduling, and exacting material and energy balances (Wang et al., 2020). Sudan spends a significant amount of foreign currency to import citric acid from various countries, including Saudi Arabia, China, India, Germany, Kenya and the United States. Given the increasing domestic demand for citric acid in sectors such as food, beverages, pharmaceuticals and other industries, the need to establish a local industrial production system has become evident. Therefore, this research aims to design, simulate, and optimize a citric acid production unit using molasses, providing a strategic model that supports the sustainable utilization of local agro-industrial byproducts and contributes to meeting future national demands.

MATERIALS AND METHODS

Materials

The following raw materials (Molasses and Nutrients) 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.

Software and Tools

In this project, SuperPro Designer® (Version 4.53) was utilized to simulate and analyze the downstream recovery process of citric acid production from molasses. The simulation methodology was based on defining the main process assumptions, material and energy balances, unit operation specifications, operating conditions, equipment capacities, and process constraints according to the experimental data and process requirements. All initial data required for the simulation were obtained from previous laboratory experiments and relevant literature sources. (Intelligen, 2002).

Methods

The analyses of (pH, Brix, Reducing Sugar (RS), Total Reducing Sugar (TRS), determination of Sucrose, Pol.) were conducted on the molasses sample obtained from the Kenana Sugar Factory, Sudan. All laboratory procedures were carried out within the Kenana Ethanol Plant laboratory located on the premises of the Kenana Sugar Company.

Process Description for Citric Acid Production from Molasses using *Aspergillus niger*

The production of citric acid from molasses involves a microbial fermentation process using the filamentous fungus *Aspergillus niger*. The process consists of several main stages: preparation of the fermentation medium, inoculum development, fermentation, separation of fungal biomass and recovery of citric acid.

Mathematical Models of Citric Acid Production

Mathematical models play a key role in analyzing and interpreting the behavior of citric acid production throughout both fermentation and downstream processing stages. These models are designed to capture the interactions between substrate utilization, microbial growth, and product synthesis through stoichiometric equations and material balance principles. In addition, they support the estimation of reaction kinetics, process productivity, and the overall efficiency of various operations within the production system. The main mathematical models applied in this study are presented below.

1. Fermentation Stoichiometric Reaction

From your process data, the balanced equation remains:

$2C_6H_{12}O_6+7.5O_2 \rightarrow C_6H_8O_7+8H_2O+6CO_2$ …………………………………… (1)

2. Substrate Consumption Rate

$dS/dt = -1/ Y_{X/S} * dx/dt$ …………………………………… (2)

Where:

- dS/dt: Substrate concentration
- $Y_{X/S}$: Biomass yield coefficient on substrate
- dx/dt: Biomass Growth Rate

3. Product Formation Rate (Luedeking–Piret Model)

$dP/dt = \alpha \, dx/dt + \beta X$ …………………………………… (3)

Where:

- dP/dt: Product Formation Rate
- α: Growth-associated product formation coefficient
- β: Non-growth-associated product formation coefficient
- X: Biomass Concentration

4. Yield Coefficients

Product Yield (Y_{P/S}):

$Y_{P/S} = P/S$ …………………………………… (4)

Where:

- $Y_{P/S}$: Product yield coefficient
- P: Amount of citric acid produced
- S: Amount of substrate consumed

5. Citric Acid Productivity

$Productivity = P/t$ …………………………………… (5)

Where:

- t: Fermentation Time

6. Oxygen Consumption Rate

$OUR = q_{O2} X$ …………,,,,…………………………… (6)

Where:

- OUR: Oxygen uptake rate
- q_{O2}: Specific oxygen consumption rate
- X: Biomass concentration

7. Solvent Recovery Efficiency

Recovery = (MIBK Recovered / MIBK Input) * 100%…………………………… (7)

ISSN 2689-5331 • Volume 9, Issue 2, 2026 • pp. 102–119

Process Description for Citric Acid Production in SuperPro Designer Software

Start -> All Programs -> Super Pro Designer V 4.53

Select the Batch in the Plant Operation Mode window and click (OK).

The production of citric acid in SuperPro Designer® involves a series of biochemical and downstream processing steps modeled to simulate industrial-scale operations. The process begins with the preparation of the substrate, typically molasses or glucose solution, which serves as the carbon source for microbial fermentation.

The overall chart of this study is represented in Figure (1) below:

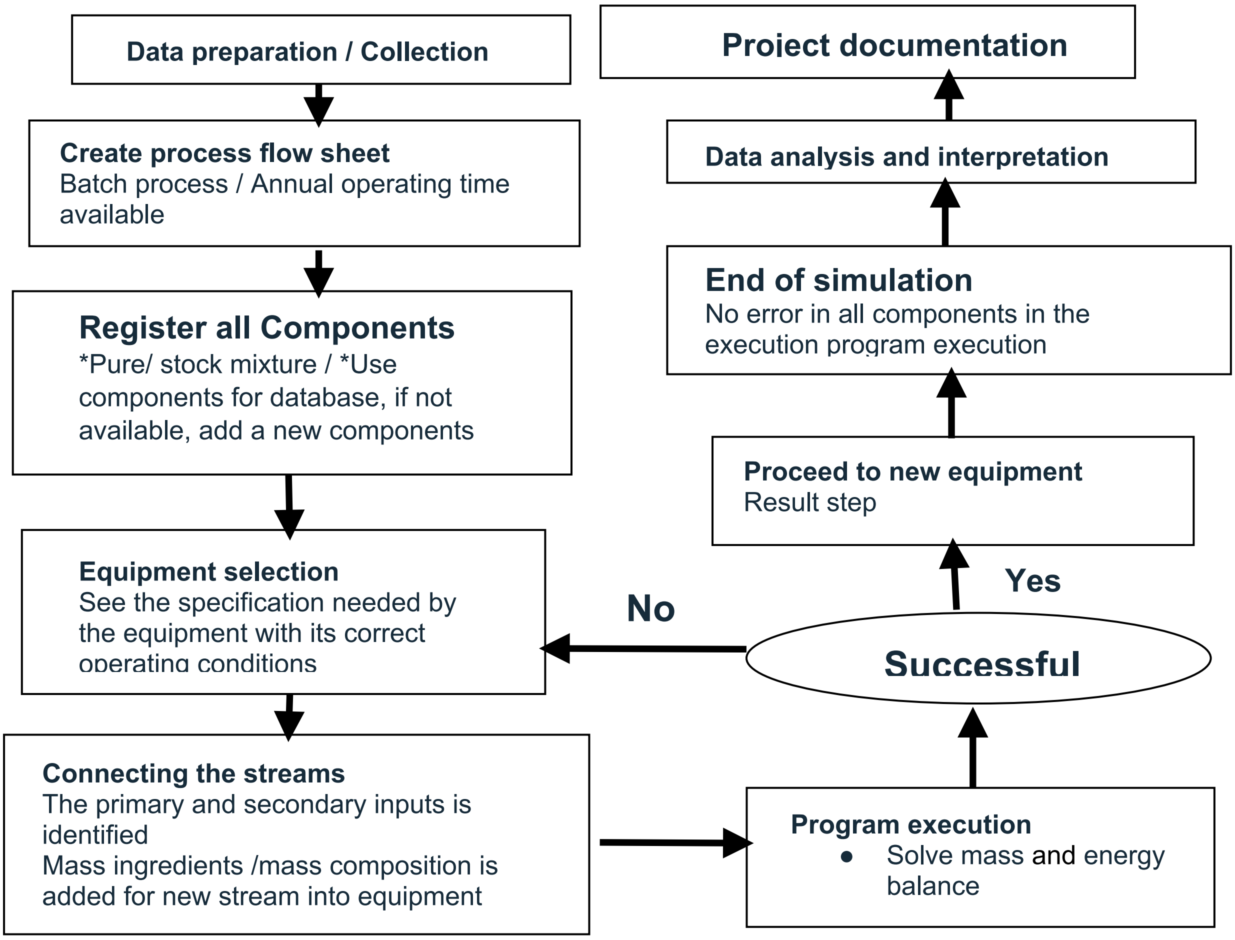

Figure 1: Overall flowchart of the study

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ISSN 2689-5331 • Volume 9, Issue 2, 2026 • pp. 102–119

The following Figure (2), shows the addition of streams to the unit operation.

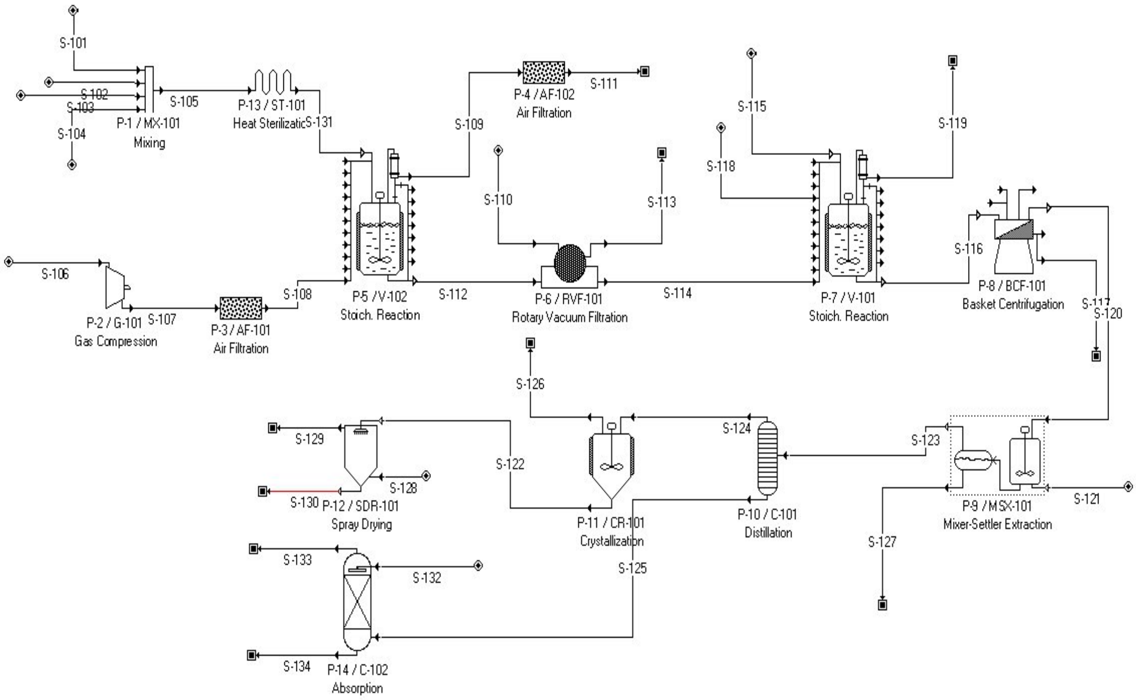


Figure (2): The add Streams to the units operation using SuperPro Designer Software (Version 4.53)

RESULTS AND DISCUSSIONS

The following Table 1, shows the results of the physical and chemical properties of the molasses analysis.

Table 1: Physical and Chemical Properties of Molasses Analysis

Ash	Total sugar	Sucrose	R.S.	Brix	Pol	Purity
13.00	50.53	32.4	18.3	35.07	29.58	84.07
13.21	50.24	32.76	17.23	34.94	29.59	84.069
13.105	50.385	32.58	17.765	35.005	29.585	Average =84.0695

The results in Table 1 indicate that the molasses sample used as a carbon source for *Aspergillus niger* fermentation exhibits relatively stable physical and chemical properties, making it suitable for citric acid production. The average ash content (13.10%) suggests the presence of essential minerals, which, while beneficial for fungal metabolism, require careful control to avoid inhibitory effects. The high total sugar content (50.39%), dominated by sucrose (32.58%), provides a rich energy source for fermentation. The reducing sugars (17.77%) fall within the optimal range to support fungal growth without leading to undesirable byproducts. In addition, the Brix (35.01), Pol (29.59), and Purity (84.07%) values reflect a high-quality molasses sample with a high proportion of fermentable sugars and minimal impurities. This enhances fermentation efficiency and reduces the need for extensive pretreatment.

Simulation Results using SuperPro Designer

This section presents key visual outputs from the SuperPro Designer simulation. These include flow diagrams, process streams, and utility consumption charts, which provide further insights into the dynamics and efficiency of the citric acid production process.

Mass balance for key components of citric acid production from molasses by *Aspergillus niger*, per batch, is shown in Table 2 below:

Table 2: Mass Balance for Key Components (Per Batch):

Component	Input (kg)	Output (kg)	Notes
Molasses	7507.5	-	Main carbon source
Water	10500	-	Dilution and fermentation
Nutrients	105	-	Essential minerals and vitamins
Aspergillus niger	52	-	Inoculum for fermentation
Air to the compressor	40282.19	-	Aeration during fermentation
MIBK (Solvent)	1208.657	984.4 (Recovered)	99.05% recovery using distillation

Table 2 illustrates the material balance for citric acid production using *Aspergillus niger*. Molasses (7507.5 kg) was the main carbon source, while water (10,500 kg) ensured adequate dilution and microbial activity. Small amounts of nutrients (105 kg) and inoculum (105 kg) supported optimal fermentation. Aeration with 40,282.19 kg of air maintained essential aerobic conditions. The extraction process using MIBK demonstrated high efficiency, with 99.05% of the solvent recovered, highlighting the effectiveness of the separation unit and contributing to process sustainability.

The following Figures 3 and 4, show the composition of the Sterilized Medium Stream to the unit operation.

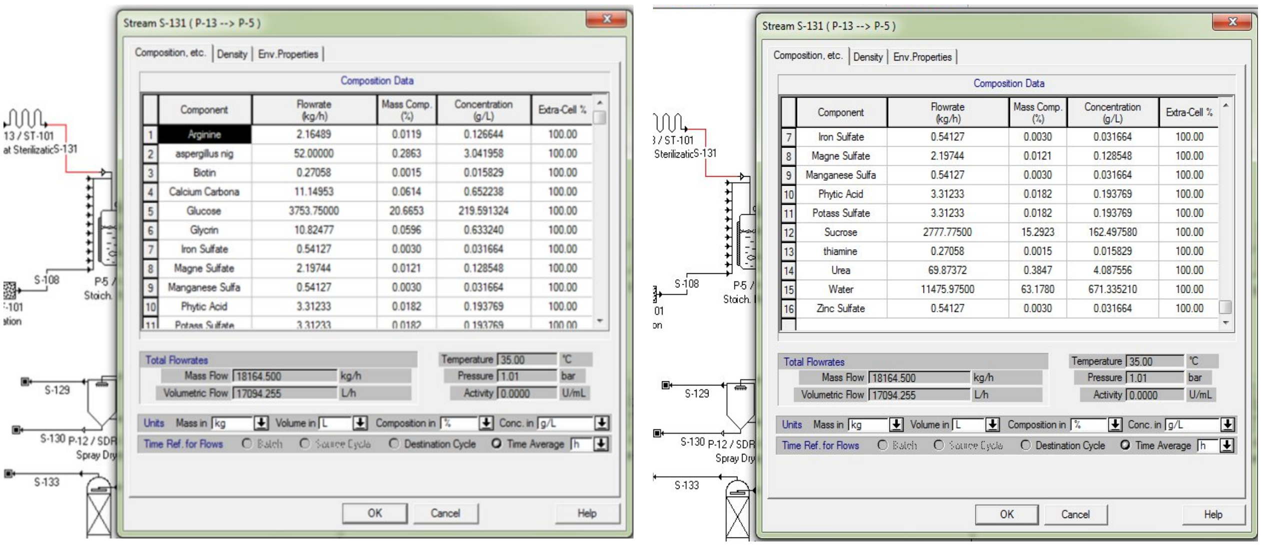


Figure 3 and 4: Composition of Sterilized Medium Stream Entering the Fermenter

The stream shown in Figures 3 and 4 represents the final composition of the fermentation medium after passing through the sterilization unit. At this stage, the molasses (7507.5 kg/hr), water (10500 kg/hr), and nutrients (105 kg/hr) have been homogenized and thermally treated to eliminate microbial contamination. This sterilized stream is critical in ensuring aseptic conditions inside the fermenter, preventing unwanted microbial interference and promoting optimal conditions for *Aspergillus niger* proliferation.

The following Figure 5, show the compressed and Filtered Air Stream Entering the Fermenter

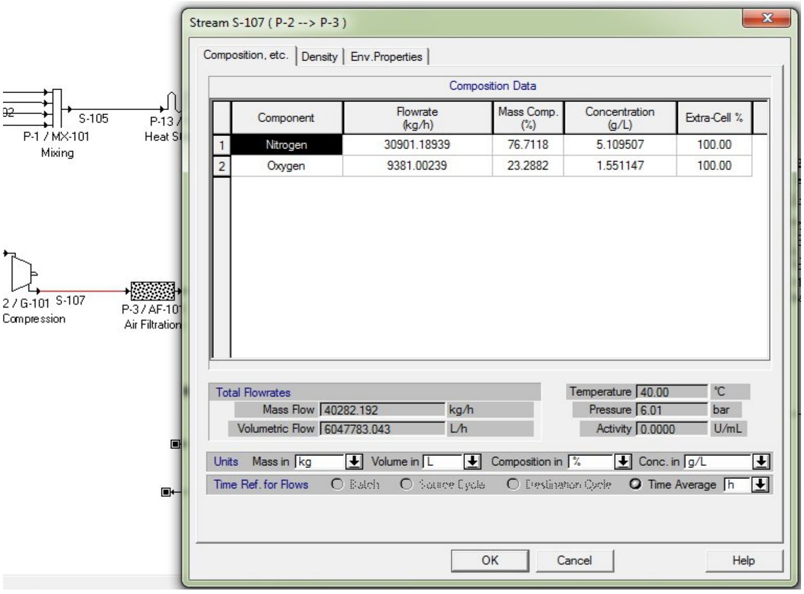


Figure 5: Compressed and Filtered Air Stream Entering the Fermenter

The above Figure 5, Stream S-107: represents the compressed air supplied to the air filtration unit, composed mainly of nitrogen (76.71%) and oxygen (23.29%), reflecting the natural atmospheric air composition without gas enrichment. It flows at 40,282.19 kg/hr, at 6.01bar and 40°C, providing suitable conditions for aerobic fermentation. The high volumetric flow (>6 million liters/hour) ensures efficient aeration within the bioreactors, maintaining optimal dissolved oxygen levels to enhance citric acid production.

The following Figures 6 and 7, show the fermentation broth stream leaving the fermenter1, 2

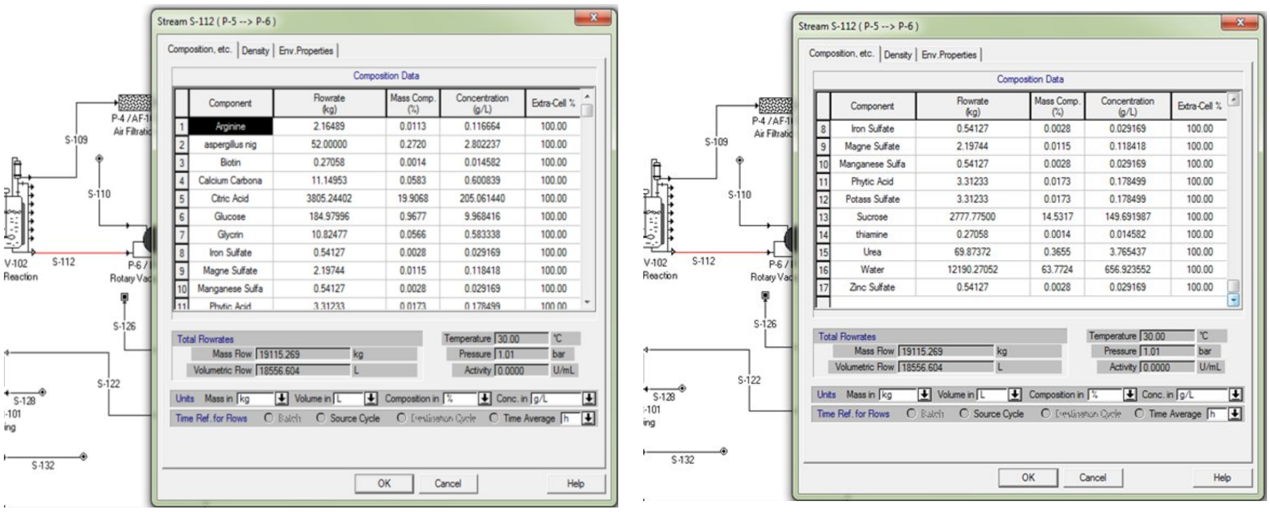
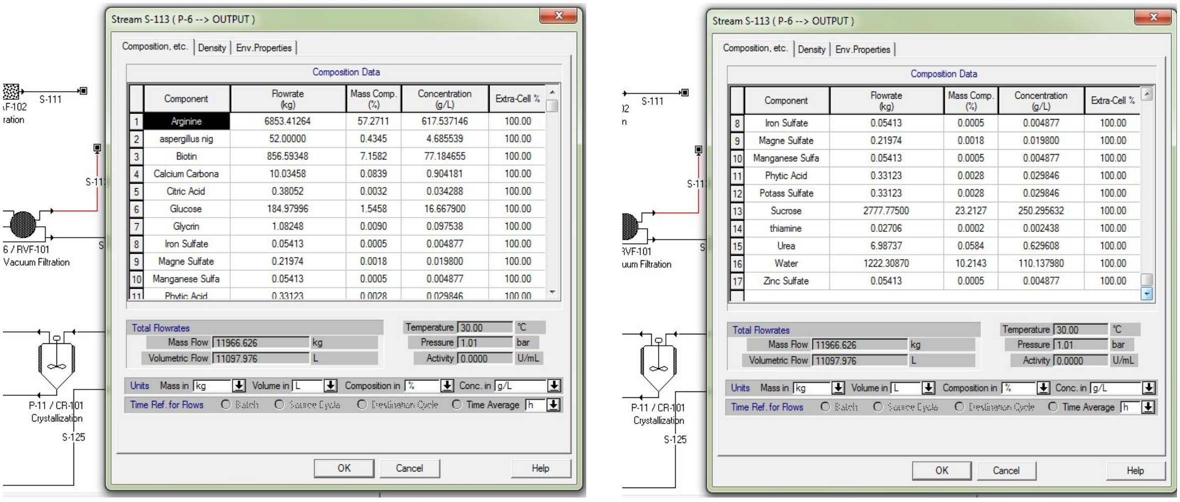


Figure 6 and 7: Fermentation Broth Stream Leaving the Fermenter1,2

African Journal of Agriculture and Food Science
ISSN 2689-5331 • Volume 9, Issue 2, 2026 • pp. 102–119

Figures 6 and 7 show Stream S-112, the fermentation medium prepared for *Aspergillus niger* cultivation. It contains: Carbon sources (sucrose, glucose, glycerin) for energy and growth, Urea as the nitrogen source for protein synthesis, Essential minerals and vitamins (Zn, Mg, Fe, biotin, thiamine), Water as the main solvent (>63%), Operating conditions of 30°C and 1.01 bar.

The following Figures 8 and 9, show the Biomass Cake Stream discharged from the Top of the Rotary Vacuum Filter1



Figures 8 and 9: Biomass Cake Stream Discharged from the Top of the Rotary Vacuum Filter1

Figures 8 and 9 illustrate the biomass cake on the rotary vacuum drum and the discharge stream (S-113) post-processing. Key findings include: Arginine sharply increased (617.53 g/L), indicating it is the primary product. *Aspergillus niger* remained constant, suggesting it hasn't been separated yet. Glucose levels were mostly unchanged, possibly due to incomplete consumption or post-addition. Citric acid concentration dropped drastically, likely due to consumption or removal. Biotin concentration rose, likely due to accumulation or concentration effects. Total mass flow decreased significantly, indicating water or byproduct removal during processing.

The following Figure 10, shows the Stream collected from the bottom of the Rotary Vacuum Filter

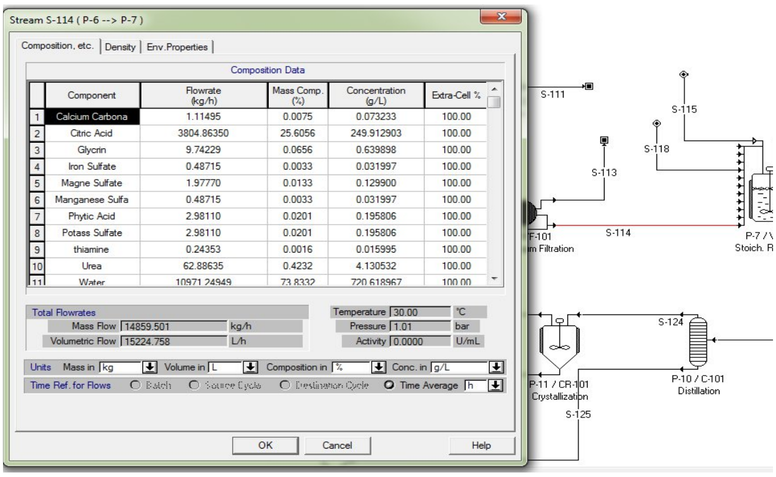
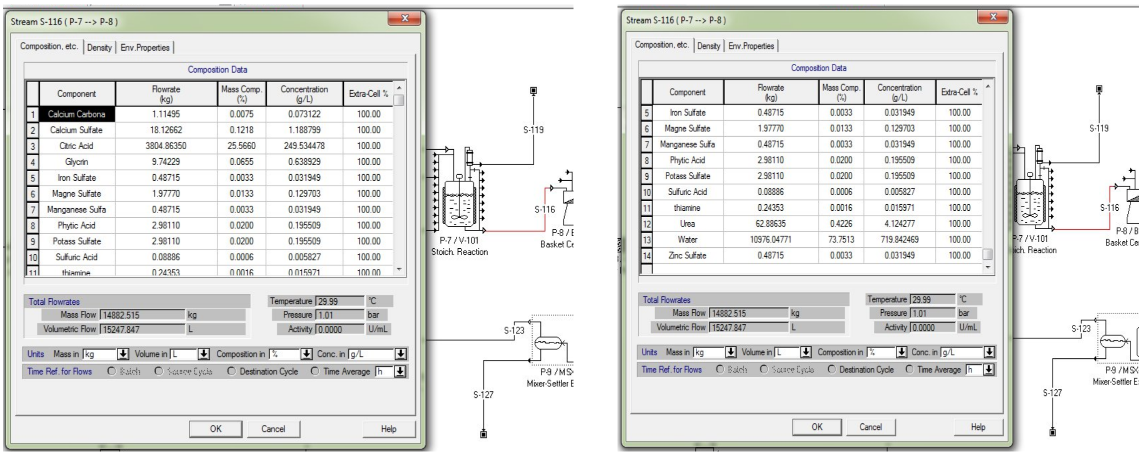


Figure 10: Stream Collected from the Bottom of the Rotary Vacuum Filter

ISSN 2689-5331 • Volume 9, Issue 2, 2026 • pp. 102–119

Figure 10 illustrates the filtered broth, which exits from the bottom of the vacuum filter. This stream contains: The bulk of citric acid produced (~3804.8 kg/hr) low suspended solids.

This stream is forwarded to the extraction stage, typically using MIBK solvent. Its composition and clarity directly affect extraction efficiency and solvent recovery performance.



Figures 11 and 12: Treated Broth Stream After pH Adjustment and Precipitation1, 2

Figures 11 and 12 show the stream exiting the second fermenter after sequential addition of $Ca(OH)_2$ and H_2SO_4. This treatment: Neutralizes citric acid-induced acidity, Precipitates impurities (phosphates, proteins, metals), Forms calcium citrate for easier separation, prepares the broth for solvent extraction (e.g., MIBK). The resulting broth has a near-neutral pH (5.5) with reduced contaminants. Monitoring ensures correct chemical dosing and readiness for efficient citric acid recovery.

The following Figure 13, shows the Solid-Rich Stream Discharged from the Basket Centrifuge

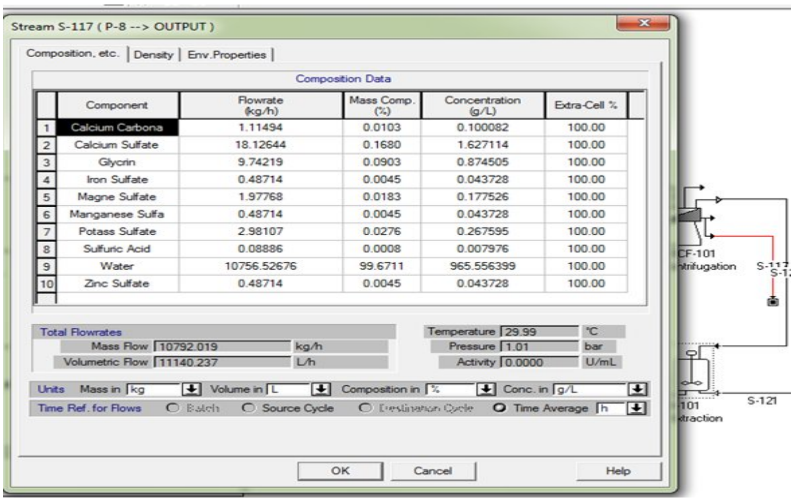


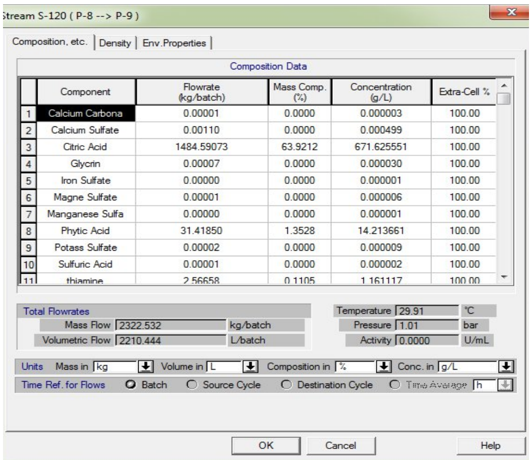
Figure 13: Solid-Rich Stream Discharged from the Basket Centrifuge

Figure 13 represents the bottom stream of the basket centrifuge, containing the solid-phase residue resulting from centrifugal separation. This figure shows the composition data for the output stream (S-117) from the fermentation feed in the citric acid production process. The

ISSN 2689-5331 • Volume 9, Issue 2, 2026 • pp. 102–119

total mass flow rate is 10,792.02 kg/hr, with water making up the majority (over 99.67%). Key nutrients and additives include: Calcium Sulfate (18.13 kg/hr), Glycerin (9.74 kg/hr), Potassium Sulfate (2.98 kg/hr), Magnesium and Manganese Sulfates, Iron and Zinc Sulfates, and Sulfuric Acid in small amounts. These nutrients are essential for the growth of *Aspergillus niger* and effective citric acid production. The temperature is approximately 30**°C**, which is ideal for fungal fermentation.

The following Figure 14, shows the Clarified Citric Acid Stream


Stream S-120 (P-8 --> P-9)
Composition, etc. | Density | Env.Properties
Composition Data

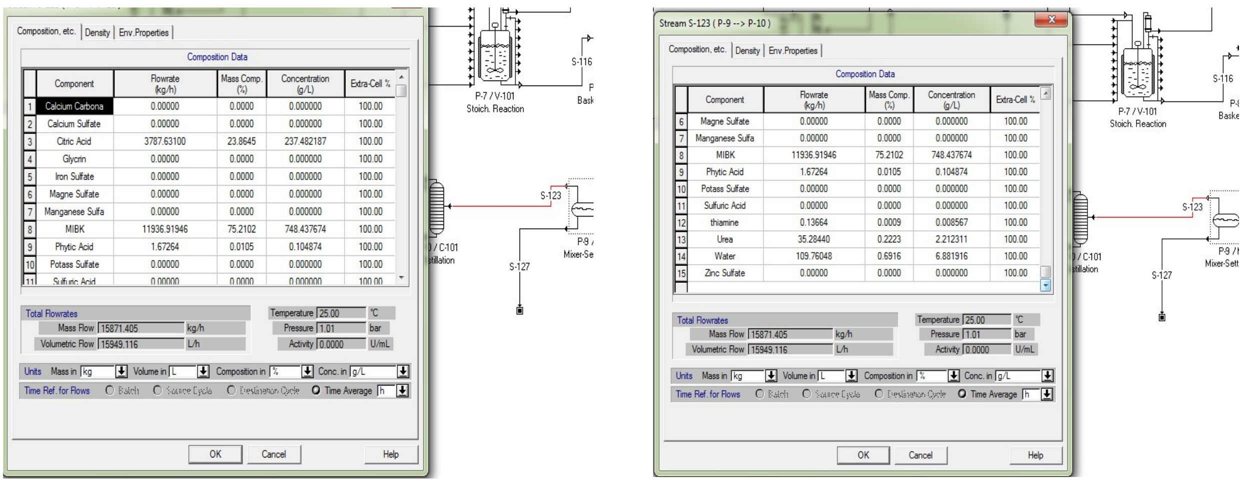
	Component	Flowrate (kg/batch)	Mass Comp. (%)	Concentration (g/L)	Extra-Cell %
1	Calcium Carbona	0.00001	0.0000	0.000003	100.00
2	Calcium Sulfate	0.00110	0.0000	0.000499	100.00
3	Citric Acid	1484.59073	63.9212	671.625551	100.00
4	Glycrin	0.00007	0.0000	0.000030	100.00
5	Iron Sulfate	0.00000	0.0000	0.000001	100.00
6	Magne Sulfate	0.00001	0.0000	0.000006	100.00
7	Manganese Sulfa	0.00000	0.0000	0.000001	100.00
8	Phytic Acid	31.41850	1.3528	14.213661	100.00
9	Potass Sulfate	0.00002	0.0000	0.000009	100.00
10	Sulfuric Acid	0.00001	0.0000	0.000002	100.00
11	thiamine	2.56658	0.1105	1.161117	100.00

Total Flowrates
Mass Flow 2322.532 kg/batch
Volumetric Flow 2210.444 L/batch
Temperature 29.91 °C
Pressure 1.01 bar
Activity 0.0000 U/mL
Units Mass in kg Volume in L Composition in % Conc. in g/L
Time Ref. for Flows Batch Source Cycle Destination Cycle Time Average h
OK Cancel Help

Figure 14: Clarified Citric Acid Stream

The figures 14 present the composition of Stream S-120, the output stream after a post-treatment step in the citric acid production process. This stream likely follows pH neutralization and impurity precipitation, as evidenced by the chemical composition and physical parameters. Key observations include: Citric Acid Flow rate: 1484.59 kg/batch Concentration: 671.63 g/L Mass Composition: 63.92%. This high concentration confirms that the stream is rich in citric acid, indicating a successful fermentation and downstream concentration phase. The broth is likely ready for solvent extraction (e.g., using MIBK). Process Conditions: Temperature: 29.91 °C Pressure: 1.01 bar These are mild, near-ambient conditions, suitable for subsequent solvent extraction steps and for minimizing citric acid degradation. Flow Data**:** Mass Flow: 2322.53 kg/batch Volumetric Flow: 2210.44 L/batch

The following Figures 15 and 16, show the Organic Phase Stream Rich in Citric Acid Extracted by MIBK 1, 2


Composition, etc. | Density | Env.Properties
Composition Data

	Component	Flowrate (kg/h)	Mass Comp. (%)	Concentration (g/L)	Extra-Cell %
1	Calcium Carbona	0.00000	0.0000	0.000000	100.00
2	Calcium Sulfate	0.00000	0.0000	0.000000	100.00
3	Citric Acid	3787.63100	23.8645	237.482187	100.00
4	Glycrin	0.00000	0.0000	0.000000	100.00
5	Iron Sulfate	0.00000	0.0000	0.000000	100.00
6	Magne Sulfate	0.00000	0.0000	0.000000	100.00
7	Manganese Sulfa	0.00000	0.0000	0.000000	100.00
8	MIBK	11936.91946	75.2102	748.437674	100.00
9	Phytic Acid	1.67264	0.0105	0.104874	100.00
10	Potass Sulfate	0.00000	0.0000	0.000000	100.00
11	Sulfuric Acid	0.00000	0.0000	0.000000	100.00

Total Flowrates
Mass Flow 15871.405 kg/h
Volumetric Flow 15949.116 L/h
Temperature 25.00 °C
Pressure 1.01 bar
Activity 0.0000 U/mL
Units Mass in kg Volume in L Composition in % Conc. in g/L
Time Ref. for Flows Batch Source Cycle Destination Cycle Time Average h
OK Cancel Help

Stream S-123 (P-9 --> P-10)
Composition, etc. | Density | Env.Properties
Composition Data

	Component	Flowrate (kg/h)	Mass Comp. (%)	Concentration (g/L)	Extra-Cell %
6	Magne Sulfate	0.00000	0.0000	0.000000	100.00
7	Manganese Sulfa	0.00000	0.0000	0.000000	100.00
8	MIBK	11936.91946	75.2102	748.437674	100.00
9	Phytic Acid	1.67264	0.0105	0.104874	100.00
10	Potass Sulfate	0.00000	0.0000	0.000000	100.00
11	Sulfuric Acid	0.00000	0.0000	0.000000	100.00
12	thiamine	0.13664	0.0009	0.008567	100.00
13	Urea	35.28440	0.2223	2.212311	100.00
14	Water	109.76048	0.6916	6.881916	100.00
15	Zinc Sulfate	0.00000	0.0000	0.000000	100.00

Total Flowrates
Mass Flow 15871.405 kg/h
Volumetric Flow 15949.116 L/h
Temperature 25.00 °C
Pressure 1.01 bar
Activity 0.0000 U/mL
Units Mass in kg Volume in L Composition in % Conc. in g/L
Time Ref. for Flows Batch Source Cycle Destination Cycle Time Average h
OK Cancel Help

Figures (15, 16): Organic Phase Stream Rich in Citric Acid Extracted by MIBK 1, 2

African Journal of Agriculture and Food Science
ISSN 2689-5331 • Volume 9, Issue 2, 2026 • pp. 102–119

Figures 15 and 16 show the organic phase stream exiting the mixer-settler extractor from the top. It shows a high concentration of citric acid (3787.63 kg/h at 237.48 g/L), indicating efficient recovery. MIBK is the dominant component (75.21%), confirming its effectiveness as the extracting agent. Water and impurities are minimal, reflecting good separation performance. The process conditions (25°C, 1.01 bar) are suitable for stable operation.

The following Figure 17, shows the aqueous raffinate stream

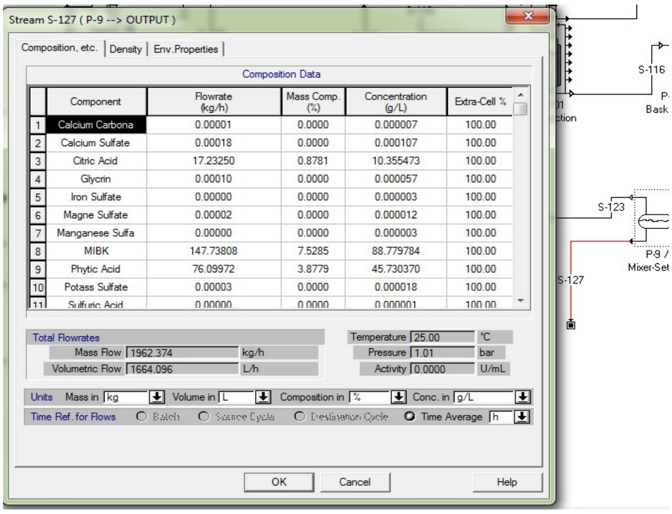


Figure (17): Aqueous raffinate stream

Figure 17 represents the aqueous raffinate from the mixer-settler unit, which includes: Residual water-soluble impurities trace citric acid not extracted (0.87%) possible nutrients, ions, or organic byproducts. This stream is typically recycled to improve overall recovery. Minimizing the citric acid in this raffinate is essential to reduce losses and maximize process economy.

The following Figure 18, shows the Overhead Distillate Stream

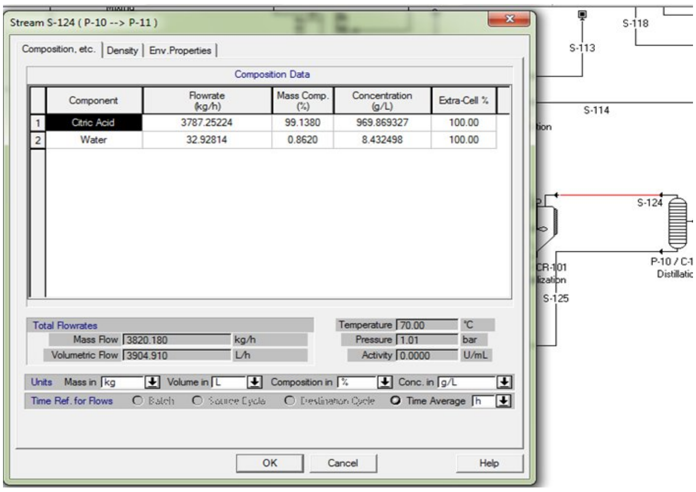


Figure (18): Overhead Distillate Stream

Figure 18 shows the overhead distillate stream, consisting mainly of citric acid dissolved in water, after the MIBK solvent has been separated and recycled**.** This stream is directed to the

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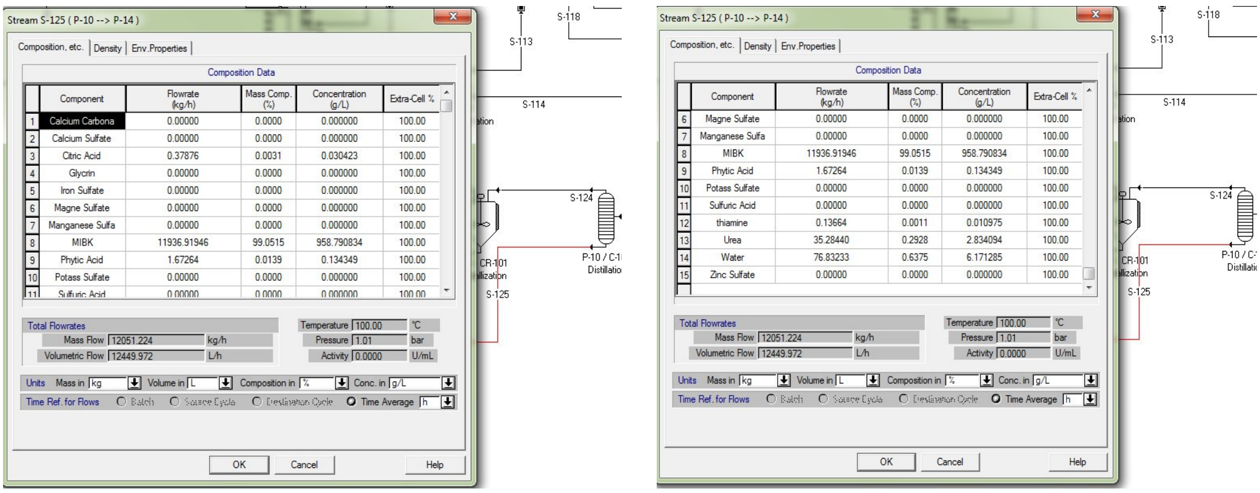
crystallization unit, where the: solution is cooled gradually to induce citric acid crystallization, the concentration and purity of the solution are keys for crystal yield and the presence of water is essential for maintaining solubility until supersaturating is reached. Efficient control of this stream ensures optimal crystal size and purity, Yield recovery rate and downstream filtration and drying performance.

The following Figures 19 and 20, show the Bottom Stream Containing MIBK Solvent 1, 2



Figures (19, 20): Bottom Stream Containing MIBK Solvent 1, 2

The Figures 19 and 20 represent the bottom stream of the distillation column, where MIBK solvent is with high concentration approximately 99.05 %.This stream is to be recovered and stored in solvent tanks, reused in the mixer-settler extraction unit, and monitored for contamination or degradation. Effective solvent recovery minimizes operational cost, environmental impact and solvent make-up needs. High recovery efficiency supports sustainable and economical process design.

The following Figure 21, shows the Stream Removed from the Top of the Crystallizer

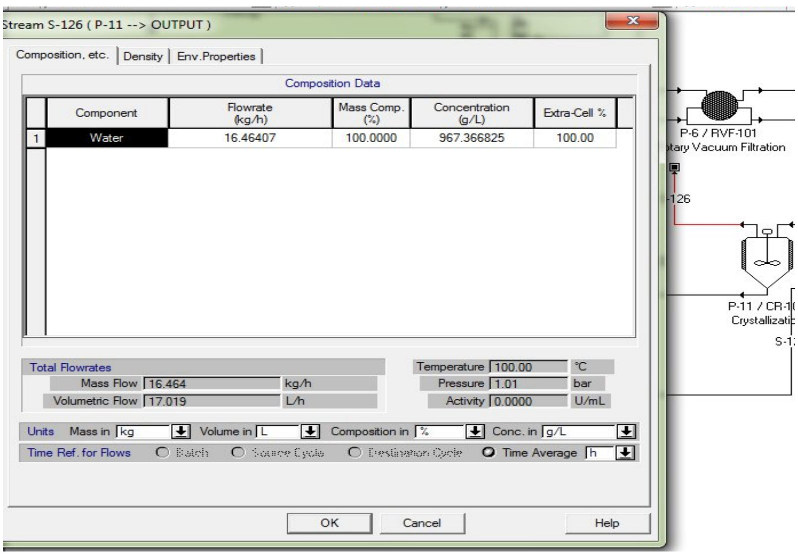


Figure (21): Stream Removed from the Top of the Crystallizer

Figure 21 shows the mother liquor stream, which is the aqueous phase remaining after crystallization. This stream typically contains: Water and residual soluble impurities (ions, un crystallized citric acid). This stream can be recycled into the process after treatment or discarded depending on purity and economics. Proper separation of this stream improves product purity, drying efficiency and waste management.

The following Figure 22, shows the Citric Acid Crystal Slurry Stream to the Spray Dryer.

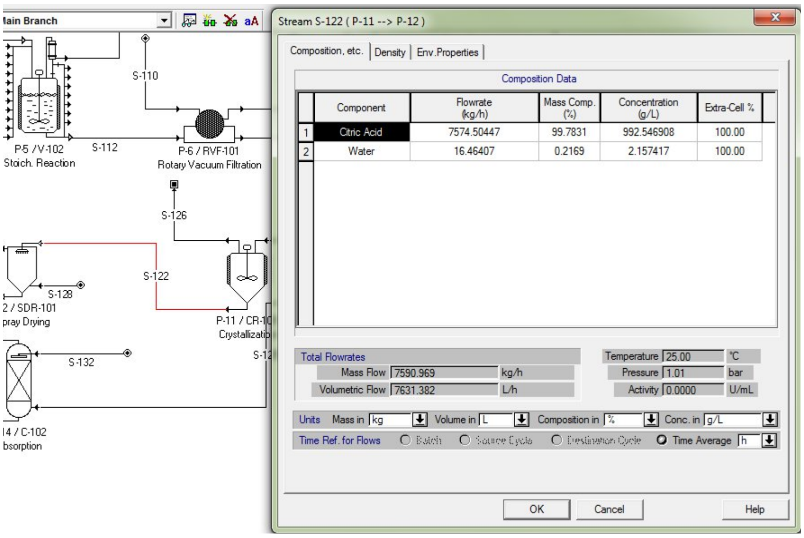


Figure (22): Citric Acid Crystal Slurry Stream to the Spray Dryer

Figure 22 represents the crystal-rich slurry exiting from the bottom of the crystallizer. It contains:

- Citric acid crystals, formed through controlled cooling and supersaturating.
- Minimal mother liquor entrained in the slurry.

This stream is sent directly to the spray dryer, where:

- The residual moisture is rapidly evaporated.
- Crystals are dried to final specifications.
- The product becomes ready for packaging,

The following Figure 23, shows the Exhaust Air and Moisture Vapor Stream.

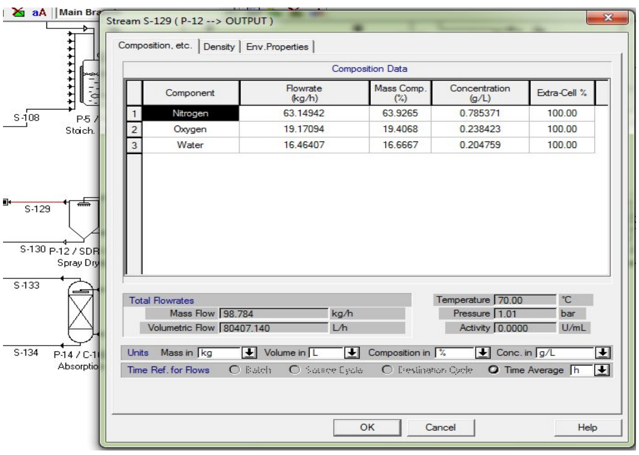


Figure (23): Exhaust Air and Moisture Vapor Stream

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Figure 23 shows the exhaust stream leaving the top of the spray dryer, which primarily includes: Moisture vapor evaporated from the slurry during drying and hot air used as the drying medium.

Key features: May contain fine dust particles, which can be recovered using a cyclone or bag filter and often directed to an air treatment or scrubbing unit before release.

Controlling this stream is essential for:

Environmental compliance (air quality), Heat efficiency of the dryer and Product loss minimization.

The following Figure 24, shows the Final Dried Citric Acid Powder Stream.

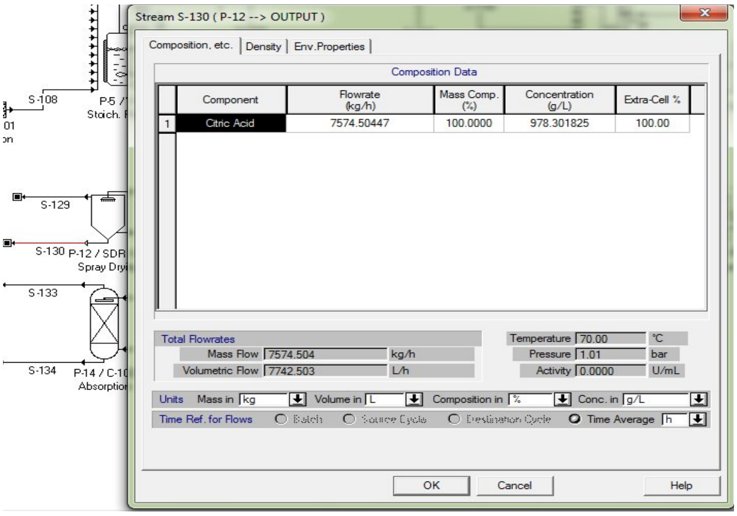

Figure (24): Final Dried Citric Acid Powder Stream

Figure 24 illustrates the final product stream exiting the bottom of the spray dryer, composed of: pure citric acid powder. (7574.5 kg/hr), Uniform particle size**,** controlled by atomizer design and inlet air temperature and Free-flowing and ready for packaging or quality testing

Proper control of this stream ensures high product yield, stable shelf life and compliance with food-grade specifications. The efficiency of the drying step strongly affects the overall process economics and product quality.

The following Figure 25, shows the Top Outlet Stream from the Absorption Unit 1.

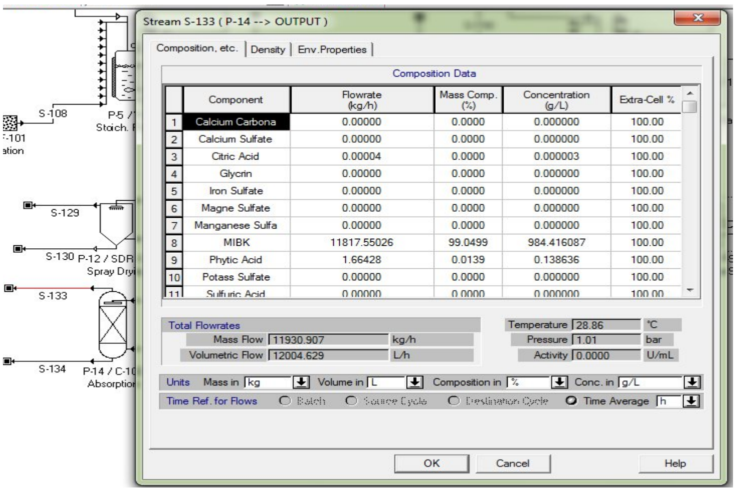

Figure (25): Top Outlet Stream from the Absorption Unit 1

Figures 25 shows that the top outlet stream contains a higher concentration of the solvent (MIBK) 99.0449%. This stream is rich in solvent and is directed to subsequent purification or distillation units for recovery and reuse.

The following Figure 26, shows the Bottom Outlet Stream from the Absorption Unit.

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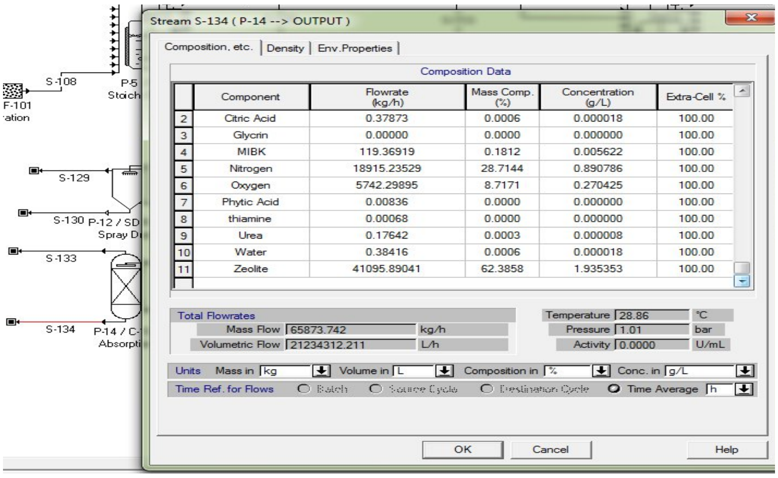

Figure (26): Bottom Outlet Stream from the Absorption Unit

Figure 26 shows that the bottom outlet stream consists mainly of water, absorbed polar compounds, and minor residuals of MIBK. This stream reflects the materials trapped or partially retained within the zeolite matrix. It is typically directed to wastewater treatment or managed via internal recycling depending on its content.

To evaluate the scalability and efficiency of citric acid production from molasses using *Aspergillus niger*, a comparative analysis was performed. Table 3 compares empirical laboratory data against mathematical model predictions and industrial simulation outputs, highlighting key shifts in yield, duration, efficiency, and economics when scaling up to an optimized industrial level.

Table 3: Comparison between laboratory Mathematical Models and simulation results

Parameter	Laboratory	Mathematical Models	Simulation
Citric Acid Yield(kg/batch)	385	2063.6	7574.5
Fermentation Time	7 days	7 days	5 days (120 hours)
Efficiency	43%	84.7%	100%
Fermentation Cost	Low due to natural nutrient alternatives	Moderate due to optimized substrate utilization and calculated nutrient demand	Accurately calculated

A comparative analysis between the laboratory, Mathematical Models, and simulation results presented in Table 3 shows significant differences between the laboratory results, mathematical models, and simulation. The citric acid yield in the simulation (7574.5 kg/batch) is many times higher than that achieved in the laboratory (385 kg/batch) due to the simulation's assumption of ideal production conditions (100% efficiency and a fermentation time shorter by 5 days). Meanwhile, the mathematical model gave an intermediate value

(2063.6 kg/batch) with an efficiency of 84.7%. The low laboratory value is attributed to real-world constraints, such as the use of low-cost but lower-concentration natural alternatives, lack of precise control over environmental factors, and a longer fermentation time (7 days) with low efficiency (43%) due to real losses in growth and metabolism. In contrast, the large numbers in the simulation are explained by the assumption of perfectly controlled conditions, absence of microbial inhibition, and use of optimal mathematical coefficients, in addition to reducing the fermentation time to only 120 hours, which maximizes productivity but may not reflect practical reality.

CONCLUSIONS

This study demonstrated the successful design, modeling, and simulation of citric acid production from molasses using *Aspergillus niger*. Laboratory results confirmed that molasses from the Kenana Sugar Factory is a suitable carbon source, and fermentation under optimal conditions (30 °C, pH 4.5, 150 rpm) produced 38.5 g/L citric acid after 7 days. The integration of mathematical modeling and SuperPro Designer® simulation improved process analysis and scale-up understanding. The mathematical model estimated a yield of 2063.6 kg per batch with 84.7% efficiency, while the simulation achieved 7574.5 kg per batch under ideal conditions with 100% efficiency and reduced fermentation time. Additionally, solvent recovery was very high (99.05%), confirming efficient downstream processing. Overall, the study shows that combining experiments with modeling and simulation is an effective approach for optimizing citric acid production, confirming its technical feasibility, efficiency, and sustainability at an industrial scale.

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